

THE AMERICAN MINERALOGIST

JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 27

SEPTEMBER, 1942

No. 9

ORIGIN OF SHAPES OF QUARTZ SAND GRAINS

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ABSTRACT

The quartz grains in many metamorphic rocks tend to be elongate parallel to the c-axis. Recently a similar elongation has been observed in the quartz grains of unmetamorphosed sandstones; also another elongation parallel to the unit rhombohedron. Current explanations ascribe these elongations to fractures parallel to these directions and differential abrasion during transport. To check these explanations three sets of experiments were carried out, with the following results: (1) There was a decided tendency for some samples of quartz to fracture parallel to the unit rhombohedron, but no sample showed a pronounced fracture parallel to the c-axis. (2) Quartz grains from weathered (but undisturbed) quartzose igneous and metamorphic rocks show a tendency to be elongate parallel to prism and unit rhombohedral faces. (3) Abrasion tests on oriented prisms show that quartz is harder on prism faces than normal thereto. It is concluded that the elongation of quartz sand grains is due to original shape rather than to fracture and differential abrasion during transport.

It has long been observed that the quartz grains in many metamorphic rocks show a tendency to be elongate parallel to the c-axis. More recently a similar elongation has been observed in the quartz grains of unmetamorphosed sandstones.

From a study of the St. Peter and Jordan sandstones Wayland¹ concluded that, "It is probable that clastic quartz grains are longer and harder in the direction of the optic axis."

Rowland² found this elongation of quartz grains to obtain in three channel sandstones and a shale of lower Pennsylvanian age. He found a similar elongation parallel to the unit rhombohedron and concluded that, "These positions can be correlated with differential hardness of quartz and are similar to positions obtained in pressure experiments."

Krynine³ describes quartz grains elongate parallel to the c-axis in the Third Bradford Sand of Pennsylvania. These grains he calls schistose

¹ Wayland, Russell G., Optical orientation in elongate clastic quartz: *Am. Jour. Sci.*, **237**, 99-109 (1939).

² Rowland, Richards A., Petrofabric determination of quartz grain orientation in sediments: Abstract. *Bull. Geol. Soc. Am.*, **51**, 1941-1942 (1940).

³ Krynine, P. D., Petrology and genesis of the Third Bradford Sand: *Penn. St. Coll. Bull.*, **29**, p. 19 and Figs. 9 and 10 (1940).

quartz, i.e., quartz derived from schist, and the elongation is ascribed to original grain shape in the schist.

Krynine has noted this elongation also in many other Paleozoic sandstones of the Appalachian Region, in the Siwalik Series of India, the Triassic of the Connecticut Valley, and in many other sedimentary rocks from various parts of the world. He offers the following summary of his observations:⁴

"(1) Quartz grains in sediment coming from igneous and metamorphic rocks have *different shapes*, but *similar* elongations (parallel to the c-axis).

"(2) Although the elongation remains constant the igneous quartz grains have a tendency to have their less elongated shape reduced still farther (from a prolate ellipsoid to a slightly prolate sphere) by differential abrasion re-inforced by selective transport.

"(3) A secondary elongation parallel to the c-axis may be produced by secondary enlargement due to deposition of secondary silica.

"(4) It is a fact that not less than 75% (and possibly much more) of the quartz in sediments come either from metamorphic rocks or from re-worked sediments which frequently have been subjected to low rank metamorphism and hence suffered elongation of quartz. Obviously then most of the quartz in sediments will have a definite shape and elongation parallel to the c-axis—which it does."

The explanations advanced by Wayland and by Rowland for the elongation of quartz grains in the sandstones appear to involve three assumptions: (1) that the grains of quartz in a sandstone are mostly fragments of larger original crystals or grains, (2) that the grains tend to break parallel to the c-axis, and (3) that the grains wear down faster in the prism zone than normal thereto.

An attempt to check these three assumptions was made by performing three sets of experiments: (1) a statistical study was made of the angles between c-axes and long axes of the grains of freshly crushed quartz, (2) abrasion tests were performed on oriented prisms cut from a single large crystal of quartz to determine the relative resistance to abrasion in three different crystallographic orientations, and (3) relation of elongation to optic axis was determined for quartz grains from badly weathered (but undisturbed) quartzose rocks.

(1) It has been assumed by various workers that quartz has a tendency to fracture parallel to the c-axis, but if there is a cleavage in that direction it is completely overshadowed by the more prominent rhombohedral cleavage. Griggs and Bell⁵ found that when a cylinder of quartz with its long axis parallel to the c-axis was splintered by compression parallel to the cylinder axis, the splinters were dominantly parallel to the crystallographic c-axis, but with cylinders of other orientations there was

⁴ Personal letter Feb. 27, 1942.

⁵ Griggs, David, and Bell, James F., Experiments bearing on the orientation of quartz in deformed rocks: *Bull. Geol. Soc. Am.*, **49**, 1723-1746 (1938).

no more tendency for the splinters to be parallel to the c-axis than normal thereto.

The case of "clastic" quartz sand can probably be more closely approached by breaking quartz grains in random orientation by crushing in a mortar. This was done for pegmatite quartz, and for fragments of a single large quartz crystal. The measurements were made by means of a universal stage from grains mounted in balsam on a microscope slide. For each grain the position of the c-axis and the longest dimension of the grain were measured and plotted on a piece of tracing paper over a stereographic net. The paper was then turned until the points representing the axis and the elongation were on the same great circle, in which position the angle between them could be read from the net. Figure 1 is

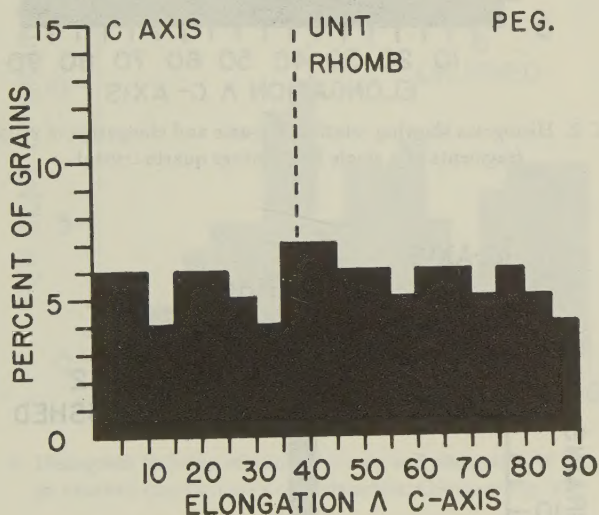


FIG. 1. Histogram showing relation of c-axis and elongation of fragments in pegmatite quartz that has been crushed in a mortar.

a histogram showing the relation of the optic axes of the grains from the pegmatite quartz to the long dimensions of the grains. There is no significant preferred orientation. Figure 2 is a histogram of the grains from the single quartz crystal from Hot Springs, Arkansas.⁶ There is a strong maximum representing the rhombohedral cleavage, but only one grain out of 100 measured is elongate parallel to the c-axis—fewer than are elongate normal thereto.

Pegmatite and vein quartz make up but a small part of sandstones,

⁶ Kindly furnished by Dr. H. D. Miser of the U. S. Geological Survey. Oriented prisms were cut from this same crystal for the abrasion tests described below (2).

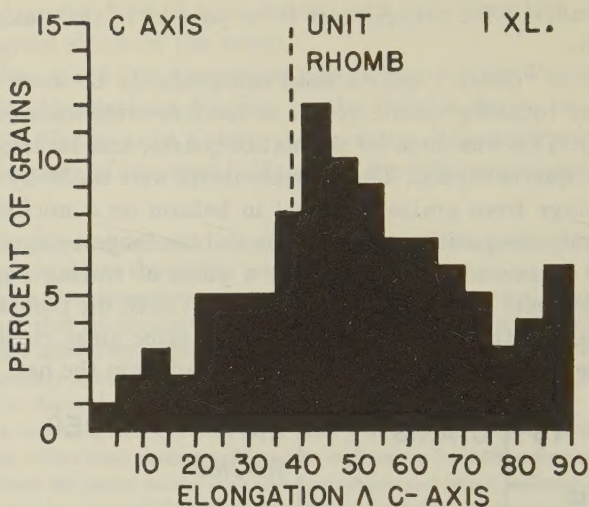


FIG. 2. Histogram showing relation of c-axis and elongation of crushed fragments of a single Hot Springs quartz crystal.

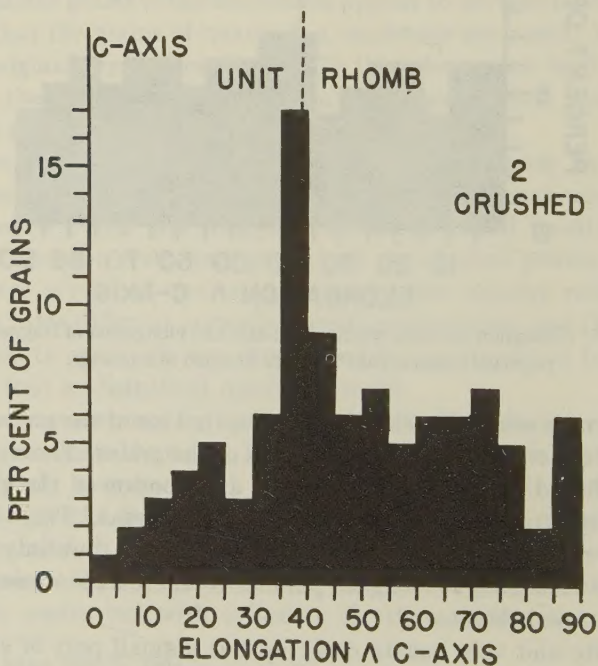


FIG. 3. Histogram showing relation of c-axis and elongation of fragments in crushed quartz from a granite gneiss. Compare Fig. 6.

most of the quartz being derived from quartzose igneous and metamorphic rocks. Therefore, quartz grains from such rocks in which an elongation of the original quartz grains parallel to the c-axis had been demonstrated [see (3), below] were crushed in a mortar, mounted, and measured as described above. Figure 3 is a histogram of the crushed grains from a granite-gneiss, and Fig. 4 is from a chlorite schist. In each there is a maximum determined by the rhombohedral cleavage. In each there are only a few grains in which the c-axis and elongation are sub-parallel, and the angular intervals between 40° and 90° average a little higher than normal. These histograms should be compared with those of un-

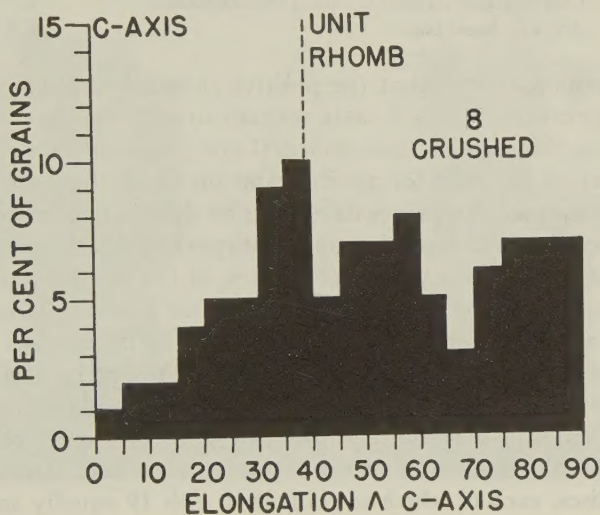


FIG. 4. Histogram showing relation of c-axis and elongation of fragments in crushed quartz from a chlorite schist. Compare Fig. 10.

crushed quartz grains from the same rocks, Figs. 6 and 10. The lack of grains elongate parallel to the c-axis in the crushed material may be due in part to the fact that many of the original grains were elongate parallel to the c-axis, hence the blows of the pestle were directed at a high angle to the c-axis. According to the work of Griggs and Bell this should produce more fractures at a high angle to the c-axes than at a low angle thereto.

(2) If quartz does not break parallel to the prism zone there must be some other explanation of the observed elongation of the quartz grains in sandstones. There are two possibilities: (a) If the quartz grains were softer in the prism zone, then differential abrasion during transport might develop grains elongate parallel to the optic axis; (b) the original grains may have been elongate parallel to the optic axis.

Ichikawa⁷ says that the experience of Japanese quartz workers shows that the artificial basal plane is much softer than the natural crystal faces, and that the "prismatic faces are harder than others." The rhombohedral faces are not mentioned specifically.

Milligan⁸ determined the impact abrasion hardness of a quartz crystal in five different directions, using a Zeiss sandblast machine. His results were as follows:

Plus prism faces	5.1
Minus prism faces	4.5
Plus rhombohedral faces	5.7
Cleavage face parallel to minus rhombohedron	4.3
Artificial basal plane	4.9

These tests indicated that the positive rhombohedral and the corresponding prismatic faces are more resistant to abrasion than is the basal plane, while the negative rhombohedral and prismatic faces are less so. If these values are valid for quartz grains on which there are few, or no definite faces, then the shapes developed by differential abrasion cannot be predicted, but will depend upon the shapes and development of faces, or surfaces approximately parallel to faces, of the original grains.

An independent test of the relative abrasion hardness of the positive prismatic and rhombohedral faces, and of the artificial basal plane was made by cutting square prisms normal to these respective faces and subjecting them to abrasion on a carborundum cup wheel, kept wet with a stream of water. The set-up is shown in Fig. 5. The upper plate has six square holes above the face of the carborundum wheel. These holes are in brass discs, each of which is graduated with 19 equally spaced divisions. The square holes in the prism holders permit the prisms to be ground in four different positions while the holders are in a given orientation.

The procedure used during abrasion was to put a prism in each hole, with pairs having a common crystallographic orientation diametrically opposed to each other. The prisms were ground for ten minutes and then each was turned 90 degrees in its holder. This was repeated until the prisms were ground in four positions. The prism holder was then turned one division and the above repeated. Each prism remained in a given hole until the holder had been turned through all 19 divisions. The prisms were then shifted clockwise to the next holder and the grinding cycle was repeated. This was continued until each prism had had a

⁷ Ichikawa, S., Studies on the etched figures of Japanese quartz: *Am. Jour. Sci.*, **39**, 455-473 (1915).

⁸ Milligan, Lowell H., The impact abrasion hardness of certain minerals and ceramic products: *Jour. Am. Ceram. Soc.*, **19**, 187-191 (1936).

grinding cycle in each holder. It is believed that this procedure effectively eliminated any differences in rate of abrasion that might have been due to position, or direction of motion of the abrasive across the faces. The prisms were made of equal cross-section and were weighted to 50 g. each during the runs.

The artificial basal plane proved to be the softest, and the rhombohedron most resistant. Another experiment was run in which the prismatic and rhombohedral faces were turned against each other with no abrasive between, until the difference in the amount of abrasion could be meas-

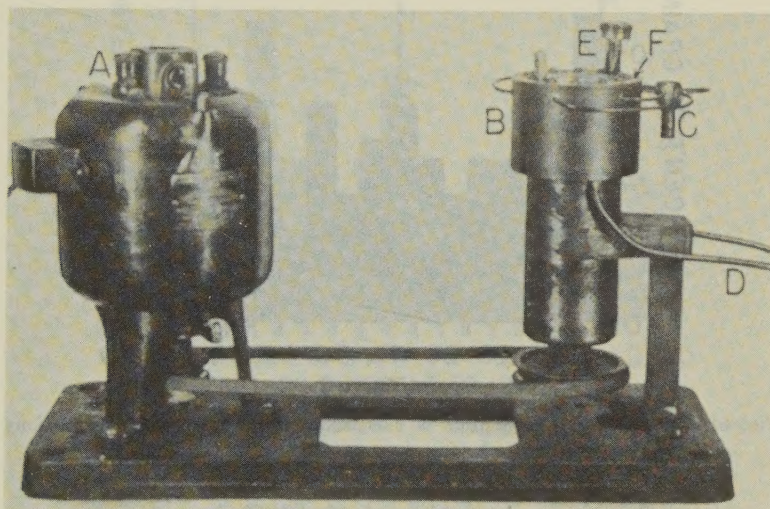


FIG. 5. Set-up for determining relative resistance to abrasion of different crystallographic directions in quartz. A, motor; B, housing for carborundum cup wheel; C, tubes for water jets; D, tubes to carry waste water away; E, quartz prism with pan for weights; F, plate carrying prism holders.

ured. It was in the same direction. These results are in accord with those of Milligan, obtained by dry impact abrasion tests. The faces of the negative rhombohedron on the crystal used were too small for the tests to be applied to them, and the negative prism faces were not tried.

If the average hardness of the prismatic faces is the greatest of any, as Ichikawa reports, then differential abrasion could not develop an elongation parallel to the optic axis. If the average hardness of the rhombohedral faces is greatest and if the original grains had only prismatic and rhombohedral faces, the elongation might be emphasized, but it would have been there all the time.

If the grains were more or less irregular and without definite crystal faces, as appears more probable from a study of quartz grains from a

granite, then elongation parallel to the c-axis would probably not be developed in any case.

(3) The remaining possibility is that the quartz grains were originally elongate parallel to the c-axis. In order to check this possibility several specimens of badly weathered granites, gneisses, and schists were collected. The material was still in place, but was so badly weathered that

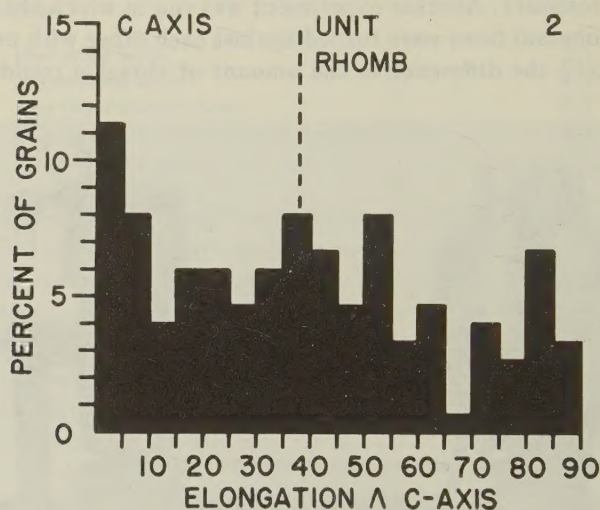


FIG. 6. Histogram showing relation of elongation and crystallographic directions in original quartz grains from a granite gneiss. Compare Fig. 3.

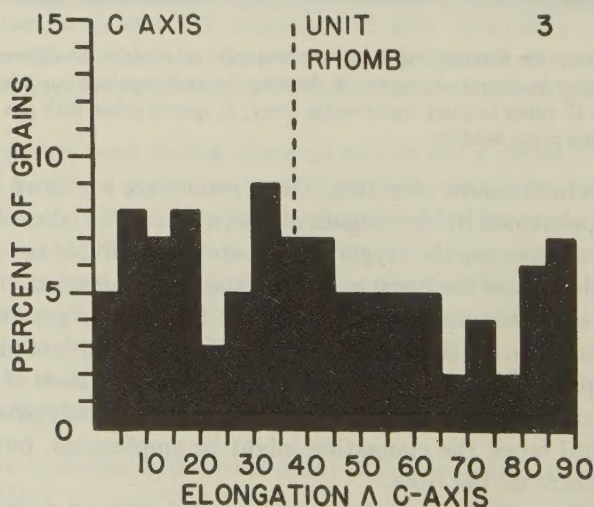


FIG. 7. Histogram showing relation of elongation and crystallographic directions in original quartz grains from a massive granite.

it could be raked out by hand. Each sample was washed free of very fine material, dried, and sieved to the approximate size of the grains in sandstones studies by Wayland. The quartz was then freed from the other minerals with mixtures of bromoform and acetone, and mounted in balsam on slides for universal stage work.

Figures 6 to 10 are histograms showing the relation of elongation of

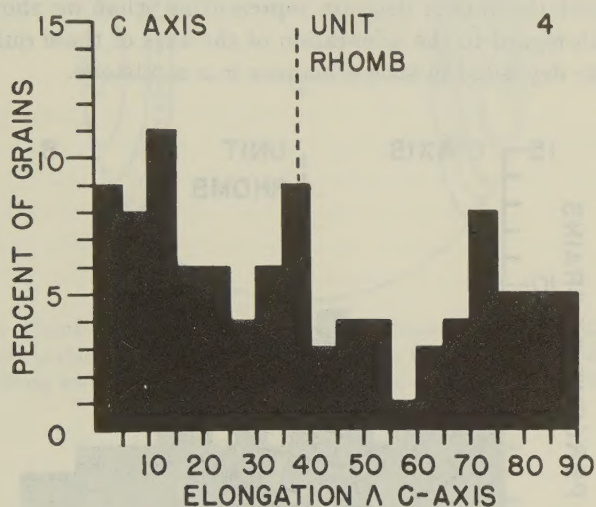


FIG. 8. Histogram showing relation of elongation and crystallographic directions in original quartz grains from a para-gneiss.

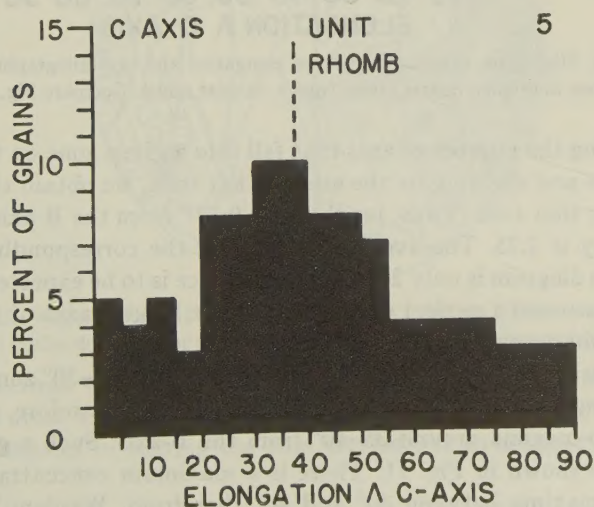


FIG. 9. Histogram showing relation of elongation and crystallographic directions in original quartz grains from a slightly gneissic granite.

original grains to the c-axis. The diagrams are by no means identical, but there is one generalization that holds good for all of them,—in each there is one maximum at or near the c-axis, and another at or near the rhombohedron.

If we assume, with Wayland, that elongate grains will roll along a bedding plane with the long axis normal to the current, then we can draw a generalized theoretical diagram representing what we should expect to find with regard to the orientation of the axes of these quartz grains if they were deposited in such a manner in a sandstone.

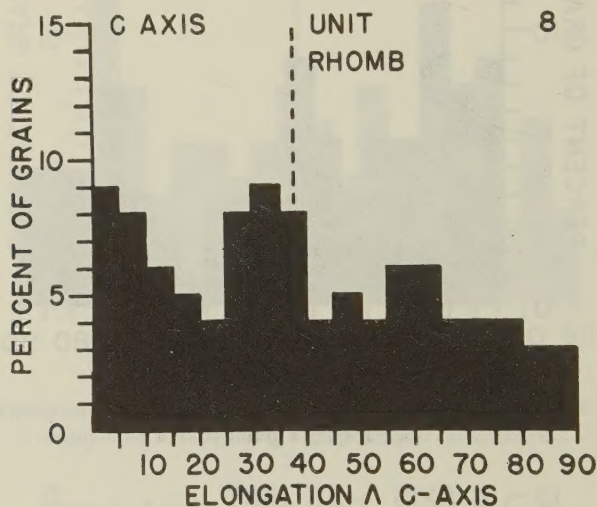


FIG. 10. Histogram showing relation of elongation and crystallographic directions in original quartz grains from a chlorite schist. Compare Fig. 4.

By taking the number of axes that fall into a given zone on the projection sphere and dividing by the area of that zone, we obtain the average density for that zone. Thus, for the zone 0–20° from the B-axis the average density is 4.25. The average density for the corresponding area on Wayland's diagram is only 2.04. This difference is to be expected, because we have assumed a perfect orientation of the longest axes of the grains, which would never be realized in nature.

The density of the zone 30–40° is higher than the 20–30° zone, because of the elongation parallel to rhombohedral faces. Therefore, we should expect sub-maxima around 35–40° from the B-axis. Such a generalized diagram is shown in Fig. 11. There is a maximum concentration at B, with sub-maxima between 30° and 40° therefrom. Wayland's diagram from the St. Peter sandstone is reproduced as Fig. 12. The sub-maxima

of the theoretical diagram are present on Wayland's diagram, but he did not consider them in his explanation of the elongate grains.

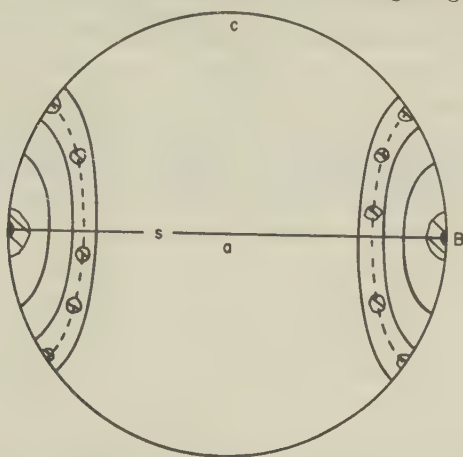


FIG. 11. Theoretical diagram showing quartz orientation in a sandstone formed of quartz grains having elongations like those shown in Figs. 6-10. It is assumed that the grains roll along and are deposited with their longest dimension parallel to the B fabric axis.



FIG. 12. Wayland's diagram of 155 quartz axes from the St. Peter sandstone. Small circles drawn in for comparison with the theoretical diagram of Fig. 11.

The maxima and sub-maxima of Wayland's diagram are somewhat displaced from their theoretical positions. This may be due to an error of a few degrees in cutting the thin section⁹, or to a slight drag during deposition.

⁹ The thin section was not cut exactly parallel to the *bc* plane. Personal communication from Wayland while this paper was in press.

SUMMARY AND CONCLUSION

These experiments show: (1) that quartz has no pronounced tendency to fracture parallel to the c-axis; (2) that elongation parallel to the c-axis is not likely to be developed by differential abrasion; (3) that unbroken and unworn quartz grains show elongations parallel to the c-axis and parallel to rhombohedral faces. These elongations are adequate to explain the shapes of quartz sand grains observed by Wayland and by Rowland and the maxima and sub-maxima of Wayland's diagram of c-axes of quartz in the St. Peter sandstone.

CRYPTOMELANE, A NEW NAME FOR THE COMMONEST OF THE "PSILOMELANE" MINERALS*

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ABSTRACT

The name cryptomelane is proposed for a distinct mineral species, hitherto included in the so-called psilomelanes. It is characterized by its distinctive *x*-ray powder diffraction photograph, the presence of essential K_2O and the low percentage of BaO .

INTRODUCTION

A comprehensive and integrated study of the manganese oxide minerals has been undertaken by the Chemical Laboratory of the Federal Geological Survey. The results to date are sufficient to characterize these minerals, but the work is still in progress and some time necessarily will elapse before publication in detail of the chemical, optical, and *x*-ray data, as well as data on thermal behavior and on paragenesis. The present paper summarizes briefly our results for the so-called psilomelanes, the commonest one of which has not hitherto been given a specific name.

The term "psilomelane" has come to be a mineralogical waste-basket; as generally used, it denotes a hard, compact manganese oxide, too fine grained to be determined accurately. "Wad" has a similar connotation, but is generally applied to soft material of low apparent specific gravity. This use of "psilomelane" as a general descriptive term is doubtless convenient in the field, but it has led to much confusion. *X*-ray study by Ramsdell¹ some years ago showed that most "psilomelanes" are crystalline and that several distinct minerals, which were not characterized chemically by him, had been grouped together under this name. Later, *x*-ray and chemical study of type specimens by Vaux² proved that the material named psilomelane by Haidinger³ is essentially a hydrous barium manganate. *X*-ray study and new chemical analyses by us confirm Vaux's findings. Ramsdell⁴ also recognized psilomelane to be a distinct mineral (his Group II). The name psilomelane should therefore be restricted to this single mineral species, essentially a hydrous barium-manganese manganate.

* Published by permission of the Director, Geological Survey, U. S. Department of the Interior, Washington, D. C.

¹ Ramsdell, L. S., An *x*-ray study of psilomelane and wad: *Am. Mineral.*, **17**, 143-149 (1932).

² Vaux, George., *X*-ray studies on pyrolusite (including polianite) and psilomelane: *Mineralog. Mag.*, **24**, 521-526 (1937).

³ Haidinger, William, Mineralogical account of the ores of manganese: *Trans. Royal Soc. Edinburgh*, **11**, 119 (1831).

⁴ Ramsdell, L. S., *op. cit.*, p. 145.

Some so-called "psilomelanes" have proved to be braunite, hausmannite, or pyrolusite. In addition to these, the following minerals have been identified among the "psilomelanes" studied, the new name cryptomelane being applied to the commonest of these crystalline "psilomelanes," which is characterized by the presence of K_2O with little or no barium.

- | | |
|--|-----------------------------|
| 1. Cryptomelane, about 60% of the samples. | |
| 2. Psilomelane, about 30% of the samples. | |
| 3. Hollandite, | } about 10% of the samples. |
| 4. Coronadite, | |
| 5. Ranciéite, | |
| 6. Lithiophorite, | |

The new name cryptomelane here given for the most abundant of these minerals is derived from the Greek words meaning hidden and black, and seems appropriate, as the identity of this common black manganese mineral has been lost within the group of such minerals. Ramsdell⁵ also found this mineral to be the most common of the "psilomelane" minerals, and therefore referred to it as "true psilomelane." On the basis of priority, however, the name psilomelane should be restricted to the mineral so named by Haidinger; Ramsdell's term "true psilomelane" should be dropped.

DESCRIPTION OF CRYPTOMELANE

X-ray Crystallography. Ramsdell⁶ recognized that a "barium-free psilomelane" was a distinct mineral species on the basis of *x*-ray photographs. He⁷ has determined the cell size and tabulated the powder diffraction data in his table.

The *x*-ray data obtained by Richmond agree closely with those of Ramsdell. These data were derived from Weissenberg photographs taken on a cleavage fragment of the mineral from Tombstone, Arizona. Richmond's results are:

$$\begin{array}{ll} a_0 = 9.82 & c_0/a_0 = 0.288 \\ c_0 = 2.83 & \end{array}$$

It was not possible to determine the space group although the extinctions definitely indicate a body centered lattice.

The powder and Weissenberg photographs of cryptomelane are nearly identical with those of the triclinic, pseudotetragonal hollandite. Frondel and Heinrich⁸ have already shown that hollandite and coronadite are

⁵ Ramsdell, L. S., *op. cit.*, pp. 144-145.

⁶ Ramsdell, L. S., *op. cit.*, p. 145.

⁷ See this issue, page 611.

⁸ Frondel, Clifford, and Heinrich, E. W., New data on hetaerolite, hydrohetaerolite, coronadite and hollandite: *Am. Mineral.*, **27**, 48-56 (1942).

isostructural. Cryptomelane, therefore, must be isostructural with both hollandite and coronadite.

The content of the unit cell, on the basis of the analyses given below and the x -ray data is, at the present time, undetermined. This is due primarily to our lack of knowledge of the valencies of the manganese in these minerals. Additional information must be obtained before any definite composition can be given for cryptomelane.

Chemical Composition. Four of the analyses of cryptomelane made in the course of our work are given in Table 1. ZnO is present in appreciable amounts in two samples. A little cobalt and copper are also present; other analyses indicate several per cent of cobalt. The water content is variable. X -ray powder pictures of the residues from the water determination (Penfield method) are identical with those of the original samples. The water is therefore regarded as non-essential. The literature contains many analyses close to those given in Table 1.

Physical Properties. The appearance of cryptomelane shows the bewildering diversity that has made identification of the members of this group of minerals so difficult. Most commonly it occurs as fine-grained masses with noticeable conchoidal fracture. Less commonly it is botryoidal. Massive cleavable varieties are not common, but have been found, as have radial fibrous varieties that grade into distinct individual fibers. The fine-grained, cleavable, and fibrous varieties are all shown on a single specimen from Tombstone. All three give identical x -ray patterns.

The color on fresh fracture is usually steel-gray to bluish-gray, varying to dull black, and it tarnishes to a dull grayish-black. The streak of the mineral is brownish-black, the shade varying somewhat, but distinctly blacker than that of manganite or braunite, and distinctly browner than that of pyrolusite or psilomelane. The hardness is 6 to $6\frac{1}{2}$, but the apparent hardness, particularly of massive or fibrous varieties, may be much lower, even 1.

Identification. X -ray powder pictures are the only certain means of identification of the "manganese oxide" minerals. The streak is helpful, but must be used with caution. A flame test, made by introducing the powdered mineral directly into the flame on a platinum or nichrome wire, may give useful information. A strong potassium flame (use of a blue glass or Merwin screen may be necessary) is a fairly good indication of cryptomelane.

The barium manganates give little or no barium flame when tested in this way. If the powdered mineral on the wire is dipped into dilute HCl and held in the flame, a strong green flame (caused by manganese chloride is observed which disappears in a few seconds and is followed by the more persistent barium flame. The presence of barium is best confirmed by precipitation as sulfate.

TABLE 1. ANALYSES OF CRYPTOMELANE (M. Fleischer, *analyst*)

	1.	2.	3.	4.
MnO ₂ *	83.13	86.54	81.75	87.09
MnO	2.08	3.92	3.50	2.49
CuO	0.12	0.44	0.06	None
NiO	None	None	0.02	None
CoO	None	0.21	0.21	0.08
ZnO	5.23	None	None	1.69
MgO	0.05	None	0.02	0.07
BaO	0.13	1.04	None	None
SrO	None	0.21	None	None
CaO	0.27	0.30	0.28	None
Na ₂ O	0.44	0.47	0.56	0.48
K ₂ O	3.50	3.88	3.84	3.10
H ₂ O—	0.81	0.21	0.38	0.60
H ₂ O+	2.58	1.62	3.45	3.58
Al ₂ O ₃	0.37	None	1.37	0.39
Fe ₂ O ₃	0.46	0.36	4.00	0.19
SiO ₂	0.58	0.03	0.35	0.18
TiO ₂	0.01	None	None	None
P ₂ O ₅	0.07	0.19	None	None
	-----	-----	-----	-----
	99.83	99.42	99.79	99.94
G.	4.33	4.32	4.41	4.17

* Arbitrarily stated as MnO₂ as calculated from the analytically determined "available oxygen."

1. Massive cleavable, from Tombstone, Arizona, collected by A. E. Granger, Survey Laboratory, No. D-1237.
2. Massive cleavable, from Deming, New Mexico, collected by J. B. Hadley No. D-1331.
3. Fine grained, steel-gray, from the Sugar Stick prospect near Mena, Arkansas, collected by H. D. Miser, No. D-1331.
4. Extremely fine grained, black, from Philipsburg, Montana, collected by E. N. Goddard, No. D-1331.

THE UNIT CELL OF CRYPTOMELANE

LEWIS S. RAMSDELL,

University of Michigan, Ann Arbor, Michigan.

ABSTRACT

Weissenberg and powder photograph data obtained from a specimen labelled "psilomelane," from Nassau, Germany, indicate a body-centered tetragonal lattice, with $a_0=9.82\text{\AA}$, $c_0=2.86\text{\AA}$, and $c/a=0.29$. The specimen gives a negative test for barium, and conforms to the material designated as cryptomelane by Richmond and Fleischer.

In 1932 the writer reported the result of an x -ray study of a large number of specimens of so-called psilomelane.¹ On the basis of powder photographs it was established that some of the material was actually pyrolusite, or in a few cases, braunite. The remainder of the specimens gave powder patterns indicating that at least three distinct structural types were present. The type which occurred much more frequently than the other two was arbitrarily called "true" psilomelane. A second type included those specimens containing an appreciable amount of barium. Among these was a specimen from Romanèche, France. Specimens labelled "psilomelane, var. lithiophorite" made up the third type.

In 1936 Vaux² made an x -ray study of pyrolusite and psilomelane, using the name psilomelane for the material containing barium. Although he did not publish the measurements of the powder pattern, his specimens included one from Romanèche, so it is probable that they correspond to the second type referred to above. Vaux established the identity of this Romanèche material with Haidinger's original psilomelane from Schneeberg, and rightly calls it psilomelane. Vaux had material sufficiently well crystallized to make single crystal as well as powder photographs, and was able to determine the unit cell. It is orthorhombic, with $a_0=9.1$, $b_0=13.7$ and $c_0=2.86\text{\AA}$.

In the writer's original report he described a specimen from Nassau, Germany. This gave a pattern corresponding to his first type, and was unusual in that individual needles projected several millimeters from the surface of radial fibrous groups. The data here presented have been secured from this specimen. Rotation photographs were obtained from the needles, and show well defined zero and first layer lines. From the layer line spacing, the identity period along the needle axis, considered to be the c axis, is 2.86\AA , corresponding exactly with Vaux's value for psilomelane.

The first attempts to obtain Weissenberg photographs showed that the

¹ *Am. Mineral.*, **17**, 143-149 (1932).

² *Mineral. Mag.* **24**, 521-526 (1937).

needles are not individual crystals, but rather bundles of smaller fibers with more or less random orientation about the needle axis. A few needles were selected which gave some evidence of crystal faces. These were about 0.1 mm. in diameter. The faces were curved, and gave reflections over quite an angular range. After several trials, one needle was found which had sufficient parallelism of the fibers to give very crude Weissenberg photographs. The reflections are weak, few in number, and in some cases are spread over a range of 10 to 20°. However, there appears to be a definite repetition of the pattern every 90°, thus indicating four-fold symmetry. Moreover, a careful comparison of the zero and first level photographs indicates quite definitely a body-centered lattice. A value of $a_0 = 9.82\text{\AA}$ was obtained from the zero level film. This could be measured with considerable accuracy, for the spots are spread out only in a direction at right angles to the direction of measurement.

These needles, therefore, are body-centered tetragonal, with $a_0 = 9.82\text{\AA}$ and $c_0 = 2.86\text{\AA}$. This gives an axial ratio of 0.29, which is in agreement with the general rule that needle-like crystals have small axial ratios. With these values for the dimensions of the unit cell, the powder photographs could be completely indexed, and the only reflections present are those with $h+k+l=2n$, which is characteristic of a body-centered lattice. This confirmation from the powder photographs gives additional support to the Weissenberg data.

Two types of powder photographs were made, one in the usual manner from powdered material, and one from uncrushed fibers in a capillary tube. The latter, because of the preferred orientation of the c axes, show no hkl reflections, but emphasize the $hk0$ reflections, and thus had the advantage of revealing some $hk0$ reflections that were too weak to be detected on the films obtained from the powdered material. Table 1 records the film measurements, with the assigned indices and calculated spacings.

If the material in which barium is an essential constituent is called psilomelane, then this barium-free material, being both chemically and structurally different, represents a distinct mineral species. Its physical properties overlap those of psilomelane, but the x -ray data definitely distinguish the two.

Richmond and Fleischer³ have made a study of the so-called psilomelanes, including chemical analyses, and for this structural type, containing little or no barium, have proposed the name cryptomelane.

³ See this issue, page 607.

TABLE 1. POWDER PHOTOGRAPH DATA FOR CRYPTOMELANE

Reflecting planes <i>hkl</i>	Calculated spacings Å	Fibers		Powder	
		Observed spacings Å	Observed intensity	Observed spacings Å	Observed intensity
110	6.94	6.92	m	6.92	w
200	4.91	4.91	m	4.91	w
220	3.47	3.47	m	3.47	vw
130	3.105	3.11	vs	3.11	m
400	2.455	2.46	m	2.46	vw
121	2.395			2.40	s
330	2.31	2.325	w		
240	2.195	2.205	ms	2.21	w
301	2.15			2.16	w
150	1.925	1.935	m		
141	1.83			1.835	m
440	1.735	1.74	w		
350	1.685	1.69	w		
600	1.635	1.64	s	1.64	w
260	1.55	1.55	w		
251	1.54			1.54	m
002	1.43			1.43	w
170	1.39	1.40	vw		
550					
460	1.36	1.36	w		
451	1.36			1.35	m
370	1.29	1.295	ms	1.295	w
402	1.235			1.24	vw
332	1.215			1.22	vw
660	1.155	1.16	w		
561	1.15			1.15	w
152					
190	1.085	1.09	vw		
390	1.035	1.04	vvw		
4.10.0	0.91	0.92	vvw		
880	0.87	0.87	w		

The spacings given are the average of measurements made on two films, one taken on a G.E. diffraction outfit, with $\text{MoK}\alpha$ radiation, the other on a smaller camera, with $\text{CuK}\alpha$ radiation.

COMPOSITION, SPECIFIC GRAVITY AND REFRACTIVE INDICES OF RHODOCHROSITE; RHODOCHROSITE FROM BUTTE, MONTANA*

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ABSTRACT

New data on rhodochrosite are presented, including unpublished analyses. Seventy-nine analyses are calculated to MnCO_3 , FeCO_3 , MgCO_3 and CaCO_3 and are plotted in three ternary diagrams. The frequency of appearance of Ca, Fe, and Mg in significant quantities as isomorphous constituents of the 79 rhodochrosite specimens is found to be in the ratio 21:17:12. Complete isomorphous miscibility with calcite and siderite is demonstrated. The series to magnesite is incomplete.

The refractive indices and specific gravities of rhodochrosite are shown to vary directly with the composition, and to be calculable from the proportions of the four end members of the system. The composition of a specimen, however, cannot be deduced from the specific gravity and optical properties alone. The n_D of pure MnCO_3 is shown to be 1.816, and the specific gravity is 3.70. The theoretical specific gravity calculated from the molecular weight and the volume of a unit cell is considerably larger.

Rhodochrosite from Butte, Montana, is described and analyses of rhodochrosite and ankerite from Butte are given.

INTRODUCTION

In 1917 W. E. Ford¹ showed that the refractive indices and specific gravities of members of the calcite group of minerals could be calculated directly from their percentage composition with reasonable accuracy. Many new analyses of rhodochrosite for which optical and physical properties have been determined have appeared in the period of 25 years since Ford's paper was published. The interest in rhodochrosite as a source of manganese has been heightened by the present emergency, and it was in the course of an investigation of manganese reserves at Butte, Montana, with Charles F. Park, Jr., that the writer decided that further quantitative study of some of the properties of rhodochrosite might be worthwhile.

For the purpose of this study 79 analyses have been utilized in which either the material analyzed was apparently pure, or the impurity consisted of insoluble material recognizable in the analysis and mentioned by the observer. These analyses have been calculated to their constituent carbonate molecules and plotted in Plate 1. With a few exceptions, they contain MnCO_3 in excess of all other carbonate molecules. Of these 79

* Submitted for publication with the approval of the director of the U. S. Geological Survey.

¹ Ford, W. E., Studies in the calcite group: *Trans. Conn. Acad. Arts and Sci.*, **22**, 211-248 (1917).

RELATION OF G AND n_0 TO COMPOSITION

EXPLANATION OF SYMBOLS

REFRACTIVE INDEX, n_D

SPECIFIC GRAVITY, G

A, E, K, ETC.

4, 5, 6, ETC.

3 - COMPONENT

4 - COMPONENT

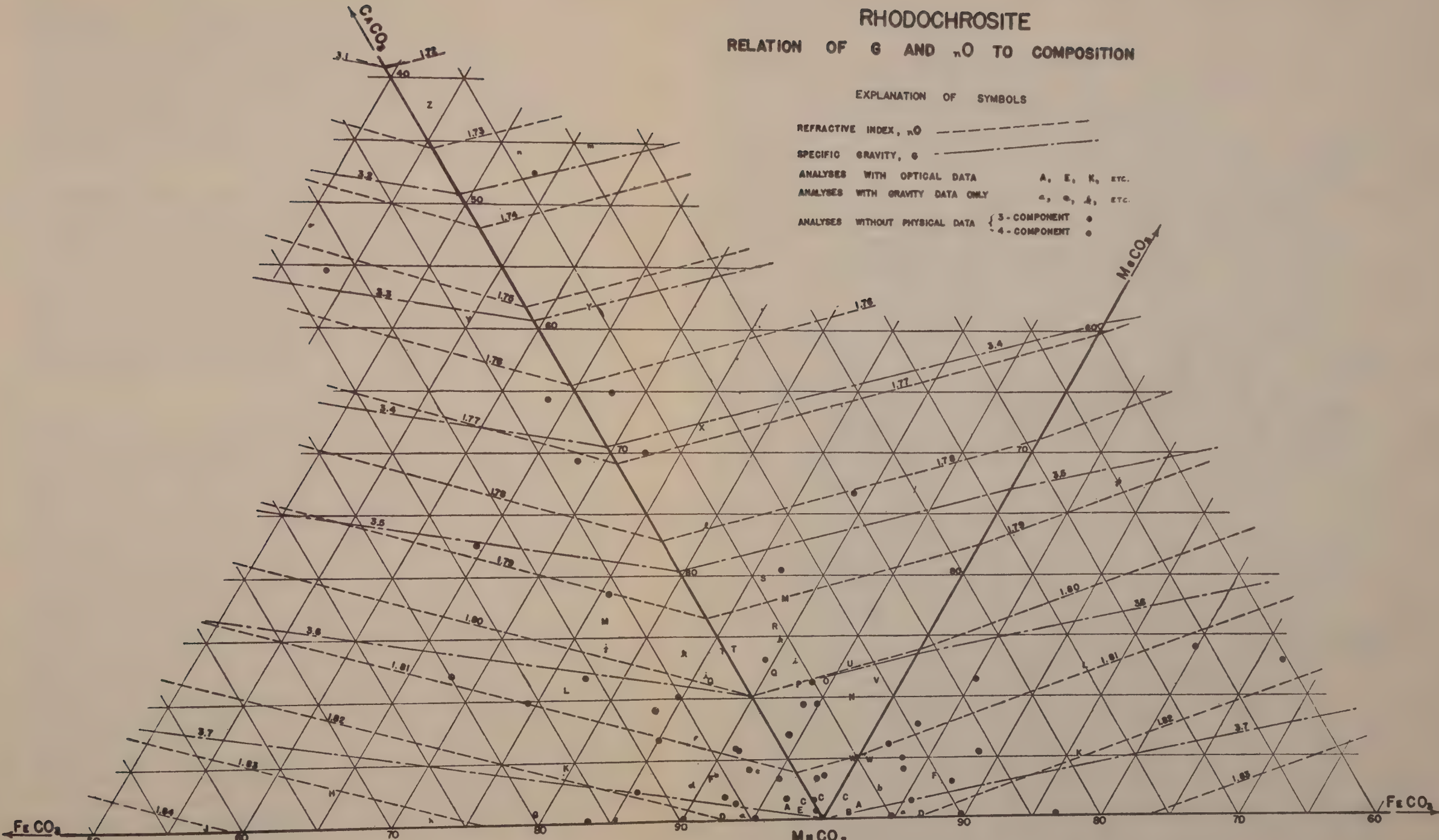


PLATE 1

acceptable analyses only the 25 reported in Table 1 were given with optical data; ten of these have not previously been published and all but two have been analyzed since 1917. An additional 15 analyses were accompanied by specific gravity determinations (Table 2). Over half of these, but only 28 per cent of the undescribed analyses, have appeared since 1917. Hence the trend toward correlation of chemical and physical data in mineralogical studies is noticeable in the rhodochrosite series, just as it is in other series which have been receiving attention in recent years.

Nevertheless, the relative scarcity of high grade analyses of pure, clean material, accompanied by carefully determined physical data, is distinctly evident in the rhodochrosite series. Investigators have also tended to ignore the local isomorphous changes in composition which are characteristic of many occurrences of the mineral. Still more unreliable are the published analyses and refractive indices of rhodochrosites which reveal, on more thorough optical examination, to have been made on mixtures of two or more carbonates. The writer has omitted a few "rhodochrosites" from consideration because of this fact.

COMPOSITION

The principal carbonate molecules present in rhodochrosite are MnCO_3 , CaCO_3 , FeCO_3 , and MgCO_3 . In a few specimens ZnCO_3 is a constituent, and one analysis contains cadmium in an unidentified form. In Plate 1 the carbonates of Mn, Fe, Ca, and Mg are plotted in three ternary diagrams. A mineral appears in two diagrams if its third and fourth most abundant metals are about equal in quantity, and it appears in all three fields if Ca, Mg, and Fe are equally abundant. The three diagrams of Plate 1 can be considered as portions of the three faces of a tetrahedron that join in an apex considered to represent 100 per cent MnCO_3 .

Of the 79 analyses plotted in Plate 1, 56 are either three-component carbonates or they contain a fourth metal in such small quantity that it may be neglected. In plotting, this fourth metal is added to the others according to the following scheme: if Ca, it is added to Mg; if Fe, it is added to Mn; and if Mg, it is distributed $\frac{3}{4}$ to Ca and $\frac{1}{4}$ to Mn. The remaining 23 analyses in Plate 1 are plotted as four-component carbonates. Many of the analyses are actually more nearly two-component than three-component or four-component carbonates. These lie near the edges of the tetrahedron whereas the three and four-component analyses lie, respectively, on the triangular faces or well within the trihedral angle forming the apex of the tetrahedron.

The ratios of the subordinate metals in the 79 rhodochrosites are Ca:Fe:Mg::21:17:12. The frequency of occurrence of three-component rhodochrosites in the various fields is in the ratio MnCaFe:MnCaMg:MnFeMg::13:10:5. These ratios should not be considered of great significance because the analyses do not constitute a representative sample of all known rhodochrosites, nor are they proportioned correctly among the districts that they represent.

ISOMORPHISM

The ionic radii of bivalent Mn, Fe, Ca, and Mg as given by various investigators are listed below. From these it would seem that Fe could

	Goldschmidt ^a	Pauling ^b	Zachariasen ^c
Ca	1.06 Å	.99 Å	.99 Å
Mn	.91	.80	—
Fe	.83	.75	—
Mg	.78	.65	.71

^a Goldschmidt, V. M., *Faraday Soc. Trans.*, **25**, 253 (1929).

^b Pauling, Linus, *Jour. Am. Chem. Soc.*, **49**, 763 (1927).

^c Zachariasen, W. H., *Zeits. Krist.*, **80**, 146 (1931).

most easily substitute for Mn in rhodochrosite, and that Mg could substitute somewhat more readily than Ca.

The MnCO₃-FeCO₃ series appears to be completely miscible. Ford² had noted a considerable break in the series between 50 and 70 per cent MnCO₃, but analyses *H* and *J* from Ouray and Leadville, Colorado, fall in this zone.

In the MnCO₃-CaCO₃ series Ford³ deduced from a study of molecular volumes, rhombohedral angles, and analyses, that only comparatively small amounts of other molecules would be found replacing CaCO₃. Of these he considered MnCO₃ the most likely to replace CaCO₃ isomorphously because of the closest relation between molecular volumes and plane angles of the rhombic faces. By means of an x-ray study and new analyses, Krieger⁴ later showed complete isomorphism in the series from CaCO₃ to analysis *Z* which is 42 per cent MnCO₃. The series is completed through specimens *T* from Batesville, *Y* from Japan, *X* from Tennessee and others here assembled, indicating that Ca and Mn may substitute for each other in any proportion. Specimens *T* and *X* were studied optically by the writer and were seen to consist essentially of

² Ford, W. E., *op. cit.*, pp. 219-220.

³ Ford, W. E., *op. cit.*, p. 218.

⁴ Krieger, Philip, Notes on an x-ray diffraction study of the series calcite-rhodochrosite: *Am. Mineral.*, **15**, 23-29 (1930).

single carbonate minerals, variable within limits but not composite. However, it is well to point out that many of these analyses which complete Krieger's series are not of the very best material. Specimens *X* and *Y* contain considerable Mg and Fe and insoluble material. Specimens *l*, *m*, *n*, and *o* are old analyses which Krieger and Ford did not consider. Ford mentions specimen *l* but classes it as exceptional. In summary, the MnCO_3 - CaCO_3 series is well demonstrated at the manganocalcite end by Krieger, and somewhat substantiated in the range from 42 to 85 per cent MnCO_3 by the present study.

The series MnCO_3 - MgCO_3 is incomplete. The magnesite highest in manganese quoted by Ford⁵ contains 13.33 per cent of MnCO_3 and 16.99 per cent FeCO_3 . Twelve other analyses of manganoan magnesite contain less than 3.5 per cent MnCO_3 . At the rhodochrosite end of the MnCO_3 - MgCO_3 series, with the exception of specimen *p*, the highest MgCO_3 content is 9.4 per cent in specimen *V*. In only one rhodochrosite in nine is MgCO_3 the second most abundant constituent. Specimen *p* (Table 2) with 27.5 per cent MgCO_3 is from Hambach (Nassau), Germany, and was analyzed in connection with a study of the thermal dissociation of rhodochrosite. The material is not described, but the analysis should probably be accepted because the oxides calculate directly to carbonates and the only impurity seems to be 0.74 per cent SiO_2 .

REFRACTIVE INDICES

The observations of the writer indicate that many natural rhodochrosites vary in their composition and optical properties more than seems hitherto to have been recognized. This is especially true of rhodochrosite from Butte, Montana, but is equally true of many specimens from elsewhere that have come to the writer's attention. Most banded rhodochrosites have small changes in composition from band to band. Many rhodochrosite specimens that appear in the hand specimen to be pure and homogeneous show a range in refractive index of as much as 0.010 in the space of an inch or so. Single crystals may be zoned. Commonly it is not enough to make only one observation of refractive index on a single grain of an analyzed sample. Some published descriptions give indices to 0.0001 but are actually questionable at 0.01. In Table 1 those observations which were found by the writer to have been made on variable material are reported as a range rather than a single observation or an average.

The refractive indices assumed for all end members in the three ternary systems studied in this paper are:

⁵ Ford, W. E., *op. cit.*, p. 221.

	n_O	n_E
FeCO_3	1.875	1.633
MnCO_3	1.816	1.597
MgCO_3	1.700	1.509
CaCO_3	1.658	1.486

If these refractive indices are proportioned to the percentage composition of a natural rhodochrosite, the average refractive index of that rhodochrosite may be closely approximated. That this is true is shown by Table 1 and by Fig. 1, in which are plotted the calculated and observed

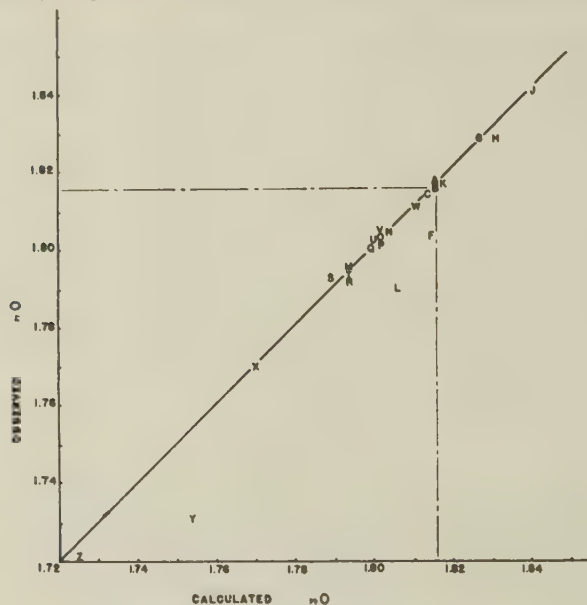


FIG. 1. Observed and calculated refractive indices.

n_O indices for all rhodochrosites listed in Table 1. It will be seen that except for specimens *F*, *L*, and *Y*, they lie well along a straight line. Specimens *L* and *Y* are described as dense and turbid, hence they were likely difficult to study optically. Specimen *F* is unaccountably low. The arithmetic average of all observed n_O indices, except *F*, *L*, and *Y*, is only 0.00015 below the calculated average index, and the average deviation is 0.00125. Ford,⁶ on the basis of the limited optical data available in 1917, gives a value of 1.817 for the n_O of pure MnCO_3 . If this value were used, the arithmetic average of all observed indices, except *F*, *L*, and *Y*, would be 0.00080 below the calculated index and the average deviation 0.00140. Hence the value 1.816 for pure MnCO_3 is more nearly correct than 1.817.

⁶ Ford, W. E., *op. cit.*, p. 242.

TABLE I. COMPOSITIONS OF 25 RHODOCHROSITES, WITH CALCULATED AND OBSERVED REFRACTIVE INDICES AND SPECIFIC GRAVITIES

	MnCO ₃	FeCO ₃	MgCO ₃	CaCO ₃	nO			nE			Sp. Gr.		
					obs.	calc.	diff.	obs.	calc.	diff.	obs.	calc.	diff.
A	96.9	1.9	.7	.5	1.817±3*	1.816	-.001	1.595±5*	1.597	+.002	3.710	3.694	-.02
B	97.8	1.6	.6	—	1.816	1.816	.000	1.600	1.597	-.003	3.691	3.699	+.01
C	97.5	.7	.8	1.0	1.8100	1.814	.00	1.5934	1.595	-.002		3.686	
					1.8135			1.5960					
					1.8194			1.6023					
D	92.9	7.1	—	—	1.818	1.820		1.5973	1.599	+.002		3.713	
E	97.9	1.2	tr	.9	1.820	1.815		1.5904	1.596	+.006	3.570	3.693	+.12
F	90.3	6.2	1.2	2.3	1.815	1.815	+.012	1.584	1.596	+.012	3.68	3.680	.00
G	79.3	19.9	—	.8	1.8279	1.827	-.001	1.6057	1.603	-.003	3.743	3.730	-.01
H	64.3	32.6	.9	2.2	1.825-	1.831	+.003		1.607			3.734	
					1.832								
J	57.6	42.4	—	—	1.840±2*	1.841	+.001	1.695	1.614		3.722+	3.780	+.06
K	78.9	15.8	2.5	2.8	1.815-	1.818	+.001		1.598			3.684	
L	75.0	12.7	5.4	6.9	1.822	1.806	+.016		1.589		3.38	3.616	+.24
M	74.7	7.2	6.3	11.8	1.790	1.794	-.001		1.581		3.51	3.551	+.04
					1.795								
N	89.6	.8	6.9	3.0	1.790-	1.804	.00	1.59	1.587	-.003	3.53-	3.616	+.0
					1.809						3.63		
O	86.7	2.0	5.7	5.6	1.803	1.802	-.001	1.588	1.586	-.002		3.607	
P	86.9	2.1	3.8	7.2	1.801	1.802	+.001	1.579	1.588	+.009		3.606	
Q	85.8	2.2	2.4	9.6	1.80	1.799	-.001		1.585			3.593	
R	81.9	2.3	4.4	11.4	1.792	1.794	+.002	1.580	1.582	+.002		3.559	
S	76.8	3.4	5.7	14.1	1.793	1.789	-.004		1.579			3.526	
					1.775-								
T	85.9	.2	.6	13.3	1.800	1.794	.00		1.582			3.565	
					1.800								
U	87.0	.3	8.3	4.4	1.791-	1.800	+.002		1.585			3.597	
					1.804								
V	88.6	.1	9.4	1.9	1.797-	1.802	-.002		1.587			3.612	
					1.811								
W	94.3	.8	4.5	.4	1.801-	1.811	.00		1.593			3.664	
					1.817								
X	65.5	2.4	7.5	24.6	1.77±	1.770	.000		1.565			3.407	
Y	53.8	4.3	4.4	37.5	1.731	1.754	+.023		1.553		3.05	3.306	+.26
Z	42.0	.1	1.7	56.2	1.721	1.725	+.004	1.534	1.533	-.001	3.143	3.134	-.01

* Range in the thousandth place.

- A. Larsen and Wherry, *Jour. Wash. Acad. Sci.*, **7**, 365–368 (1917); from the John Reed mine, Alicante, Lake County, Colorado, transparent crystals, $r/r' = 73^{\circ}10' - 20'$, anal. Wherry.
- B. Sundius, *Geol. Fören. Förh.*, **47**, H. 1, pp. 269–270 (1925); from Alma, Colorado, $r/r' = 73^{\circ}2'$, anal. Bygden. Hedvall, *ibid.*, pp. 73–80, finds thermal decomposition begins around 200° C. and dissociation is complete in the range below 540° C.
- C. Gaubert, *Bull. Soc. Franc. Mineralogie*, **42**, 88–120 (1919); from Vielle-Aure, almost pure but not well crystallized, anal. Gruner.
- D. Ortloff, *Zeits. phys. Chem.*, **19**, 215 (1896); from Biersdorf.
- E. Barić and Tućan, *Annales Geol. de la Peninsule Balkanique, Belgrad*, **8**, 129–130 (1925); from Ljubija, Bosnia, rose-colored secondary rhodochrosite on limonite.
- F. Harada (*Japan. Jour. Assoc. Min. Pet. Econ. Geol.*, **1932**), *Neues Jahrb. Min., Geol.*, Ref. 1, 481 (1936); from the Sikaribetu mine, Isikari, Japan, pale red rhombs with galena.
- G. Ford, *Trans. Connecticut Acad. Arts and Sci.*, **22**, 211–248 (1917); from Branchville, Conn., anal. Bradley.
- H. Burbank, *U. S. Geol. Survey Bull.* in preparation; from the Bachelor mine, Ouray, Colorado, salmon-pink crystalline, zoned rhodochrosite in quartz veins with sphalerite and pyrite, 2.38 per cent insoluble, anal. Murata, optical data, Wayland.
- J. Mayo and O'Leary, *Am. Mineral.*, **19**, 304–308 (1934); oligonite from the Tucson shaft, Leadville, Colorado, tiny, pale, radiating columns, specific gravity probably low according to authors, anal. O'Leary.
- K. Callaghan, *Econ. Geology*, **33**, 508–521 (1938); from the Black Boy mine, Drum Mountains, Utah, banded pink rhodochrosite, cementing dolomite breccia, anal. Bailey, optical data, Glass. Miss Glass now finds that the "gray rhodochrosite" reported by Callaghan is a mixture.
- L. Yosimura, *Jour. Fac. Sci., Hokkaido Imp. Univ.*, series 4, **4**, 313–451 (1939); from the Kaso mine, Japan, dense turbid rhodochrosite with SiO_2 , Al_2O_3 , H_2O , and insoluble totalling 10.95 per cent.
- M. Yosimura, *op. cit.*, Kaso mine, clusters of coarse, pink crystals in the interspaces between blood-red rhodonite crystals, with 5 per cent insoluble.
- N. Emma mine, Butte, Montana, deep pink, coarse, zoned cleavage rhomb, anal. Fairchild, optical data, Wayland.
- O. Ross, C. P., *U. S. Geol. Survey Bull.* in preparation; from Whitlatch dump, Austin, Nevada, 15.08 per cent insoluble, 1.04 per cent Fe_2O_3 , anal. Steiger, optical data, Glass.
- P. Ross, *op. cit.*, from Belle Wilder, Austin, Nevada, 24.45 per cent insoluble, anal. Steiger, optical data, Glass.
- Q. Ross, *op. cit.*, from Cummings lease, Austin, Nevada, 32.03 per cent insoluble, anal. Steiger, optical data, Glass.
- R. Ross, *op. cit.*, from Isabella mine, Austin, Nevada, handpicked of impurities and cleaned in heavy liquids, 4.58 per cent insoluble, anal. Wells, optical data, Glass.
- S. Ross, *op. cit.*, from Ruby Incline, Austin, Nevada, 26.12 per cent insoluble, anal. Steiger, optical data, Glass.
- T. Miser and Hewett (*U. S. Geol. Survey, Bull.* **921-A**, in preparation), *U. S. Geol. Survey, Bull.* **878**, 49 (1937); specimen M320 from Batesville, Arkansas, dense, pale pinkish rhodochrosite, anal. Wells, optical data, Wayland. Indices of most grains of the sample lie between 1.79 and 1.80. Other analyses reported are composite.
- U. Goddard, *U. S. Geol. Survey* unpublished analysis, 1940; from Algonquin mine, Philipsburg, Montana, anal. Fahey, optical data, Wayland.
- V. Goddard, *op. cit.*, from Algonquin mine, anal. Fahey, optical data, Wayland.

- W. Goddard, *op. cit.*, from Scratch Awl mine, Philipsburg, Montana, anal. Fahey, optical data, Wayland.
- X. Keith, in *U. S. Geol. Survey, Bull.* **878**, 95 (1937); from Sevier, Tennessee, impure, zoned, turbid rhodochrosite, 15.54 per cent SiO_2 , 2.42 Al_2O_3 , anal. Steiger, optical data, Wayland.
- Y. Yosimura, *op. cit.*, from the Kaso mine, Japan, dense grayish rhodochrosite replacing rhodonite; with sericite and quartz. Turbid, pleochroic, impure, with SiO_2 , Al_2O_3 , H_2O and insoluble totalling 19.26 per cent.
- Z. Krieger, *Am. Mineral.*, **15**, 23–29 (1930); from Sparta, North Carolina, anal. Shannon.

The n_E indices calculated from Ford's value of 1.597 for pure MnCO_3 differ an arithmetic average of 0.0064 from observed indices, if specimen *F* is disregarded. The average deviation is 0.0032. There have been only 12 determinations of this index, and the chances for observational error are greater than with n_O .

SPECIFIC GRAVITY

Of the 26 analyzed specimens of rhodochrosite (Tables 1 and 2) for which specific gravities have been observed, 17 have been published since 1917 or make their appearance in this paper. Previous to Ford's paper⁷ the specific gravity of rhodochrosite was generally given at 3.45 to 3.60. As Fig. 2 shows, some natural rhodochrosites do lie in this range. The value of 3.70 assumed by Ford for the specific gravity of pure MnCO_3 is substantiated by the recent additional observational data and by calculation from specific refractive indices of MnO and CO_2 and the observed index of MnCO_3 , but it is considerably lower than the theoretical specific gravity derived from x-ray data, as will be shown. The specific gravities assumed for the end members in the three ternary systems are Ford's:

FeCO_3 3.89 MnCO_3 3.70 MgCO_3 2.96 CaCO_3 2.715

In calculating specific gravities for specimens *b* and *l* the specific gravities of ZnCO_3 and CdCO_3 (?) were taken as 4.45 and 5.6, respectively.

Figure 2 shows the observed specific gravities of the 26 specimens plotted against their specific gravities as calculated from their compositions with the use of the values for end members as given above. In a number of specimens the observed specific gravity falls short of the calculated specific gravity, and in many others they are equal, but in none are they substantially greater. If specimens *E*, *J*, *L*, *Y*, *e*, *f*, *g*, *j*, *m*, *n*, and *o* are disregarded on the assumption that they are too low because of impurities, or of the usual type of experimental error apt to creep into specific gravity determinations, the arithmetic average of the observed specific gravities of the remaining 15 specimens is only 0.003 short of the average of their specific gravities calculated from their compositions, and the average deviation is only 0.015.

⁷ Ford, W. E., *op. cit.*, pp. 215–228.

TABLE 2. COMPOSITIONS OF 15 ADDITIONAL RHODOCHROSITES, WITH CALCULATED AND OBSERVED SPECIFIC GRAVITIES

	MnCO ₃	FeCO ₃	MgCO ₃	CaCO ₃	obs.	calc.	diff.
a	94.2	5.8	tr	—	3.69	3.711	+ .02
b	94.9	1.2	2.2	0.2	3.70	3.710	+ .01 { .2 ZnCO ₃ 1.3 CdCO ₃ (?)
c	93.3	2.7	0.1	3.9	3.698	3.666	— .03
d	89.2	7.8	0.3	2.7	3.668	3.685	+ .02
e	90.5	5.7	—	3.8	3.552	3.674	+ .12
f	87.5	5.6	—	6.9	3.312	3.643	+ .33
g	85.1	14.4	—	0.5	3.59	3.724	+ .13
h	72.3	27.1	—	0.6	3.76	3.745	— .01 $r \wedge r' = 73^\circ 11'$
i	84.7	2.4	4.5	8.4	3.58	3.588	+ .01
j	76.5	8.3	3.9	11.3	3.51	3.577	+ .07
k	82.2	3.1	4.3	10.4	3.553	3.571	+ .02
l	73.6	0.3	3.7	20.1	3.47	3.493	+ .02 2.3% ZnCO ₃
m	38.4	6.8	11.0	43.8	3.06	3.200	+ .14
n	41.8	0.7	5.5	52.0	3.052	3.149	+ .10
o	40.4	11.4	—	48.2	3.09	3.247	+ .16
(p)	(65.0)	(7.5)	(27.5)	(—)		(3.511)	
(q)	(6.9)	(5.3)	(33.3)	(54.5)	(2.94)	(2.93)	(— .01) mangan- ankerite

- a. Kunz, *Am. Jour. Sci.*, 3d series., **34**, 477–478 (1887); from the John Reed mine, Alicante, Lake County, Colorado, rich red, transparent rhombohedrons, pleochroic, n_O salmon pink, n_E light yellow, anal. Mackintosh.
- b. Zsviny (*Földtani Közölny, Budapest, 1927*), *Min. Abs.*, **3**, 508 (1928); from Rákoš, Slovakia, small scalenohedrons on limonite.
- c. Barić and Tučan, *Annales Geol. de la Peninsule Balkanique, Belgrad*, **8**, 129–130 (1925); from Ljubija, Bosnia, light rose-colored secondary rhodochrosite on limonite.
- d. Barić and Tučan, *op. cit.*, from Ljubija, Bosnia, brown rhodochrosite on limonite.
- e. Veselý (*Rozpravy, České Akad., 1922*), *Min. Abs.*, **2**, 142 (1923); from Litošice, Bohemia.
- f. Veselý, *op. cit.*, from Chvaletice, Bohemia.
- g. Sandberger, *Neues Jahrb. Min.*, **2**, 37–43 (1892); from Arzberg, Bohemia, frail, transparent spherical aggregates with radial structure, anal. Hilger.
- h. Brush and Dana, *Am. Jour. Sci.*, 3d series, **18**, 50 (1879); from Branchville, Conn., pink rhodochrosite in lithiophilite, and white or slightly pink granular masses with apatite and quartz, anal. Penfield.
- i. Yosimura, *Jour. Fac. Sci., Hokkaido Imp. Univ.*, series 4, **4**, 313–451 (1939); from the Kaso mine, Japan, pink rhodochrosite ore with tephroite, 2.7 per cent SiO₂.
- j. Yosimura, *op. cit.*, from the Kaso mine, Japan, pink rhombohedra in drusy quartz veins, 2 per cent insoluble.
- k. Kersten, (*Jour. pr. Chem.*, **37**, 163, 1887), *Dana System*, V ed., 691 (1884); from Voightsb-
erg, Saxony.

- l. Browning, *Am. Jour. Sci.*, 3d series, **40**, 375-376 (1890); from Franklin Furnace, N. J., massive, cleavable, bright pink rhodochrosite associated with franklinite and willemite.
- m. Bukovsky, *Zeits. Krist.*, **39**, 400 (1904); from Kuttenberg, Bohemia, reddish-white mangan-dolomite.
- n. Roepper, *Am. Jour. Sci.*, 2nd series, **50**, 37 (1870); from Stirling Hill, Franklin Furnace, N. J., delicate pink cleavage masses, with willemite.
- o. Weibull, *Tsch. Min. Petr. Mitt.*, **7**, 111 (1886); from Vester-Silfberg, Sweden, fine grained, light gray manganocalcite.
- p. Manchot and Lorenz, *Zeits. anorg. Chem.*, **134**, 297-316 (1924).
- q. Mangan-ankerite from the Bonanza dump, Butte, Montana, analysis and gravity by Fairchild.

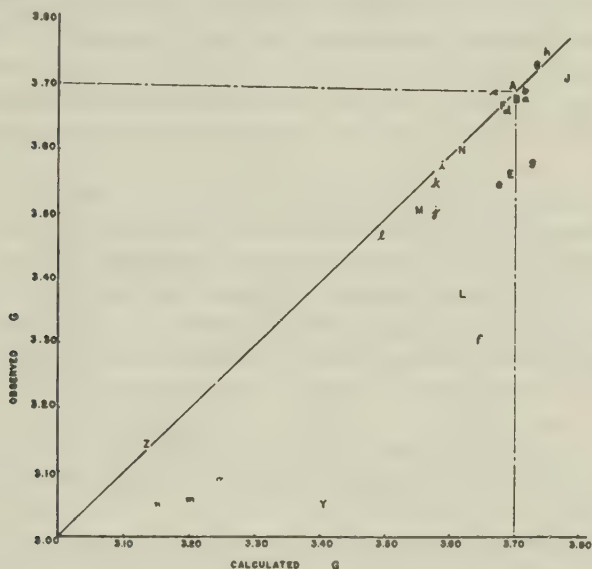


FIG. 2. Observed and calculated specific gravities.

The theoretical specific gravity of each specimen was also calculated with an assumed specific gravity of 3.71 for pure MnCO_3 . The fifteen best determinations were then found to average 0.013 below their calculated specific gravities. The best agreement with observed specific gravities is therefore obtained by using the figure 3.70 for pure MnCO_3 .

The theoretical specific gravity of pure MnCO_3 may be calculated by two independent methods. Application of the law of Gladstone and Dale, $G = n - 1/K$, where n is the mean refractive index of MnCO_3 ($\sqrt[3]{\omega^2 \epsilon}$) and K equals the sum of the specific refractive indices of MnO and CO_2 times their respective weight percentages, gives a value of 3.707 for pure MnCO_3 .

The second method, $G = \frac{(\text{Mol. wt.})(\text{No. of mols./unit cell})}{(\text{Vol./unit cell})(\text{No. of mols./gm. mol. wt.})}$, requires knowledge of the size of the unit cell of pure MnCO_3 . Unfortunately it is unlikely that the dimensions given by the various investigators of crystal structure are for pure rhodochrosite. In only one case has the unit cell of an analyzed specimen been studied.

Brentano and Adamson⁸ measured a rhodochrosite on which they had observed the specific gravity to range between 3.47 and 3.76, indicating that the material ranged in composition from ferroan to calcian or magnesian rhodochrosite. The length of an edge, a_0' , of a unit cell corresponding to a cleavage rhomb was found to be 6.064\AA , and the angle α' of a rhombic face was $102^\circ 50'$. Such a unit cell contains four molecules of MnCO_3 . From this data Brentano and Adamson calculated a specific gravity of 3.747. They may have measured a ferroan portion of their sample.

The true unit cell of rhodochrosite and of other members of the calcite group has been found by Wyckoff⁹ not to correspond with the cleavage rhombohedron but to be a steep rhombohedron which contains only two molecules. Wyckoff obtained some of the analyzed material of specimen *A* from Lake County, Colorado, and determined the length of the edge of its unit rhombohedron, a_0 , to be 5.61\AA and the rhombic face angle α to be $47^\circ 46'$. Later Wyckoff changed the a_0 value to 5.84\AA .¹⁰ Using the values 5.84\AA and $47^\circ 46'$ for the Lake County rhodochrosite and calculating the molecular weight from the analysis, the writer obtained a density of 3.785. This is higher by 0.075 than the observed specific gravity, 3.710.

Bragg¹¹ and Wyckoff¹² in their latest compilations on crystal structure give the following dimensions for MnCO_3 :

$\frac{a_0}{5.84\text{\AA}}$	$\frac{\alpha}{47^\circ 20'}$	$\frac{a_0'}{6.01\text{\AA}}$	$\frac{\alpha'}{102^\circ 50'}$
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Using the values 5.84\AA and $47^\circ 20'$ the writer obtained a theoretical specific gravity of 3.851, and using the values 6.01\AA and $102^\circ 50'$ the specific gravity is 3.837. These are much higher than observed values for rhodochrosite.

⁸ Brentano, J., and Adamson, J., Precision measurements of x-ray reflexions from crystal powders: *Philos. Mag.*, ser. 7, **7**, 507-517 (1929).

⁹ Wyckoff, R. W. G., The crystal structure of some carbonates of the calcite group: *Am. Jour. Sci.*, 4th ser. **50**, 317-320; 351-353 (1920).

¹⁰ Ewald, P. P., and Herman, C., Strukturbericht 1913 1926, *Zeits. Krist.*, 316-317 (1931). Also *International Critical Tables*, **1**, 342 (1926).

¹¹ Bragg, W. L., Atomic Structure of Minerals, *Cornell Univ. Press*, 114-116 (1937).

¹² Wyckoff, R. W. G., The Structure of Crystals, 2nd ed., *Am. Chem. Soc., Mon. Series* **19**, 275 (1931).

If we now assume that the specific gravity of pure rhodochrosite is 3.70 and its n_O is 1.816, and that the physical properties of natural rhodochrosites can be calculated from the chemical compositions, we can place on Plate 1 lines of equal specific gravity and index. On doing this we see that the reverse procedure is not possible, that is, knowing the specific gravity and the refractive indices we still cannot tell the composition, because the lines on the diagram are parallel or intersect at small angles. Simple qualitative chemical tests would serve to indicate the field in which some specimens would lie, but in most cases a quantitative analysis is necessary.

In distinguishing rhodochrosites from minerals of the siderite-magnetite series the refractive index and specific gravity data may be useful. For a given n_O the specific gravity of a magnesian siderite will be about 0.1 lower than for rhodochrosite.

Having studied the relationships of composition, specific gravity, and refractive indices of a number of rhodochrosites from a wide variety of localities, it remains to be seen in what ways rhodochrosite from Butte is similar or different from other rhodochrosites. As suggested above, it was the erratic relationship between color banding and the optical data of Butte rhodochrosite that induced this study, and it is especially because of this that the following descriptions of occurrence, mineral association, texture and isomorphism of Butte rhodochrosite are considered of interest to this paper.

RHODOCHROSITE AT BUTTE, MONTANA

The Butte district has produced over 400,000 tons of high grade rhodochrosite ore since 1917. During the present emergency lower grade ores are being beneficiated by flotation. The rhodochrosite is calcined in large rotary kilns to produce an oxide which contains about 58 per cent manganese. Most of the ore has come from the Emma mine on the Black Chief lode near downtown Butte, but rhodochrosite is common in most of the veins of the southwestern and western portions of the district.¹³

¹³ Hewett, D. F., and Pardee, J. T., Manganese in western hydrothermal deposits; Ore deposits of the western states (Lindgren Volume): *Am. Inst. Min. Met. Engr.*, 672-675 (1933). Sales, R. H., Ore deposits at Butte, Montana: *Trans. Am. Inst. Min. Met. Eng.*, **46**, 3-109 (1914). Weed, W. H., The geology and ore deposits of the Butte district, Montana: *U. S. Geol. Survey, Prof. Paper*, **74** (1912). Hart, L. H., The Butte district, Montana; Copper resources of the world: *XVI Int. Geol. Congress*, **1**, 287-305 (1935). Pardee, J. T., Deposits of manganese ore in Montana, Utah, Oregon, and Washington: *U. S. Geol. Survey, Bull.* **725c**, 141-179 (1921). Pardee, J. T., Manganese at Butte, Montana: *U. S. Geol. Survey, Bull.* **690e**, 111-130 (1918). Perry, Eugene S., The Butte mining district, Montana: *XVI Int. Geol. Congress, Guidebook* **23** (1932). Bard, D. C., and Gidel, M. H., Mineral associations at Butte, Montana: *Trans. Am. Inst. Min. Met. Eng.*, **46**, 123-127 (1914).

The most abundant minerals with which the rhodochrosite is found are quartz, rhodonite, sphalerite, pyrite, and galena. Quartz is the dominant mineral in most veins of the peripheral zone. Rhodonite is abundant in the veins of the northern part of the district. Less common mineral associates of rhodochrosite are ankerite, calcite, barite, arsenopyrite, chalcopyrite, tetrahedrite, tenantite, chalcocite and bornite.

Some of the ore shoots in the Emma mine consist almost exclusively of rhodochrosite. They seem to be localized by certain vein intersections and by flattening in the dip of the veins. Numerous smaller stringers of rhodochrosite are parallel to the main veins. Most of the walls of the rhodochrosite veins are tight and sharp. The wall rock of quartz monzonite is locally heavily sericitized, silicified and pyritized for short distances away from the veins.

Rhodochrosite is one of the latest of the primary minerals in the peripheral zone. Fracturing and brecciation preceded and accompanied its deposition. Some minor faults tend to diminish and disappear in the carbonate. Quartz and sulphides are in general earlier than the rhodochrosite and occur in part as breccia fragments cemented by rhodochrosite. Later than rhodochrosite are a few small seams of dull milky quartz with sphalerite and pyrite. Locally there are vugs lined with euhedral rhombic crystals of rhodochrosite on some of which there is deposited a layer of tiny crystals of quartz and a few small pyrite and sphalerite crystals. In the northern part of the district rhodochrosite and rhodonite are essentially contemporaneous, but both thin sections and hand specimens commonly show rhodonite to be veined and partly replaced by rhodochrosite. Hence it is probable that rhodochrosite continued to form after rhodonite.

Most of the rhodochrosite is banded, compact and crystalline, with grains ranging in size from 0.1 mm. to over 6 cm. The color ranges from deep rose to pale pinkish gray and cream. Many specimens are color-banded and some individual crystals are zoned. Some of the banding is textural, dependent on size of grain and the number and character of minute inclusions. It is evident that much of the rhodochrosite has been deposited in successive layers.

About seventy determinations of refractive index of rhodochrosite grains of all colors, grain size and associations were made on specimens from all parts of the southwestern and western portion of the district. The lowest n_O noted is 1.778 in the cream-colored band of a sharply-banded specimen from the 800-foot level of the Emma mine. The highest n_O noted is 1.815 in dense pale pink rhodochrosite from the extreme western edge of the district. The great majority of the indices lie between 1.797

and 1.810, with the average at 1.8035. Geographic location within the district has no marked correlation with indices.

In general the light or cream colored rhodochrosite bands are lower in index than the pink or rose carbonates. Some pale pink rhodochrosite bands or zones are lower in index than the deeper rose rhodochrosites but others are higher. There may be more variation in index within a color band than there is between adjacent color bands, though this is generally not true. Clearly there is considerable isomorphic variation in the Butte rhodochrosite. Plate 1 shows the great range in isomorphous changes possible in rhodochrosites within the index range noted at Butte.

Specimen *N* in Table 1 and Plate 1 is from the 1000-foot level of the Emma mine. It is a single, large, zoned crystal from a coarse-grained aggregate and has a range in color from deep to medium pink. The determinations of specific gravity were made by J. G. Fairchild using the pycnometer method and by Waldemar T. Schaller using the Berman microbalance. The partial analysis by Fairchild is MnO 55.20, MgO 3.28, CaO 1.68, FeO 0.30, ZnO none, SO₃ 0.02, insoluble 0.05, CO₂ 39.31 (calculated); total 99.84 per cent.

Two bulk analyses of Emma ore are available. Hewett and Pardee¹⁴ give the average composition of about 250,000 tons of ore from the Emma mine and indicate the molecular composition of the rhodochrosite free from impurities to be MnCO₃ 91 per cent, MgCO₃ 7 per cent and CaCO₃ 2 per cent.

The average percentage composition of 13,961 tons of rhodochrosite ore delivered to the Southern Manganese Corporation in 1918 and 1919 and the variation in monthly average analyses are given below:

	Average of 13,961 tons	Range of monthly averages
MnO	45.92	43.85-47.89
FeO	3.04	2.70- 3.44
MgO	2.92	2.39- 4.01
CaO	0.89	0.63- 1.66
SiO ₂	6.53	5.52- 9.12
Al ₂ O ₃	1.60	0.53- 2.20
BaO	none	
P	0.06	
CO ₂	27.99	
	<hr/> 88.95	

If the FeO is assigned to pyrite rather than to FeCO₃, following Hewett and Pardee,¹⁵ the molecular composition of the rhodochrosite free from impurities is approximately as follows:

¹⁴ Hewett, D. F., and Pardee, J. T., *op. cit.*, p. 674.

¹⁵ Hewett, D. F., and Pardee, J. T., *op. cit.* p. 674.

	Average of 13,961 tons	Range of monthly averages
MnCO ₃	90.7%	86.0-94.0%
MgCO ₃	7.4	6.0-10.0
CaCO ₃	1.9	1.4- 3.6

These analyses and the optical data indicate that Butte rhodochrosite is lower in iron and higher in magnesium than most rhodochrosites. The rhodochrosites of Philipsburg, Montana, specimens *U*, *V*, and *W*, have similar characteristics.

OTHER MAGANESE MINERALS AT BUTTE

In addition to the abundant rhodonite of the northern part of the district, minor quantities of mangan-ankerite, manganosiderite,¹⁶ huebnerite,¹⁷ helvite¹⁸ and alabandite¹⁹ are found. A specimen of pale pink, massive, crystalline mangan-ankerite from the dump of the Bonanza mine was analyzed by J. G. Fairchild: CaO 30.52, MgO 15.92, MnO 4.28, FeO 3.31, ZnO none, SO₃ none, insoluble none, and CO₂ 46.08 (calculated); total 100.11. The observed *n*O ranges between 1.690 and 1.698 and the calculated *n*O is 1.694. The specific gravity and molecular proportions are given in Table 2 as specimen *q*.

Greenish wolframite similar to that described as an alteration product of huebnerite by Winchell²⁰ was noted in a specimen of banded rhodochrosite from the Emma mine. The mineral occurs as extremely tiny, greenish prisms intimately intergrown with quartz. Spectrographic tests by K. J. Murata and chemical tests by Michael Fleischer showed the presence of Fe, Mn, and W. The identity of the wolframite was proved by *x*-ray powder pictures taken by W. E. Richmond.

ACKNOWLEDGMENTS

The writer is pleased to acknowledge the constructive criticism and helpful suggestions of Drs. Waldemar T. Schaller, D. F. Hewett, Charles F. Park, Jr., J. B. Mertie, Michael Fleisher, and Duncan McConnell. The Anaconda Copper Mining Company permitted the examination of the Butte carbonate ores. Persons responsible for the chemical and some of the optical data have been acknowledged throughout the text. The writer is indebted to Messrs. E. N. Goddard, W. S. Burbank, C. P. Ross, H. D. Miser, and D. F. Hewett of the U. S. Geological Survey for permission to include some of their analyses previously unpublished.

¹⁶ Pardee, J. T., *op. cit.* (Bull. 690e), p. 119.

¹⁷ Winchell, A. N., Notes on tungsten minerals from Montana: *Ec. Geol.*, 5, 158-165 (1910).

¹⁸ Hewett, D. F., Helvite from the Butte district, Montana: *Am. Mineral.*, 22, 803-804 (1937).

¹⁹ Hewett, D. F., and Pardee, J. T., *op. cit.*, p. 674.

²⁰ Winchell, A. N., *op. cit.*, p. 165.

MAGNETIC SEPARATIONS IN PETROGRAPHY

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ABSTRACT

Clean magnetic separations of mixtures of rock minerals are uncommon for several reasons including two that are important, but these have not received much attention. First, as most magnetic separators are designed, they attract larger grains more strongly than smaller grains; apparently even a difference in size of 0.03 mm. is great enough to cause trouble. Second, the different members of several isomorphous series are differently attracted by strong magnets; the series from Mg to Fe compounds shows a wide range in attractability. Magnets can probably be designed to reduce or eliminate the effect of grain-size, but one can hardly expect zoned crystals which have a range of compositions to be cleanly separated from other minerals.

THE PROBLEM

In some work done by the writer for Professor F. F. Grout at the University of Minnesota using two forms of magnetic separators, the results seemed to be peculiar in ways not clearly presented in the texts on petrographic methods. Commonly¹ an attempt is made to separate a crushed rock—a mixture of minerals—into four products of differing magnetic properties. First, a weak magnet extracts magnetite; then a stronger magnet extracts moderately magnetic minerals; and finally a very powerful magnet separates the remainder into weakly magnetic and tailings products. Some adjustments are commonly possible to adapt the magnets to the minerals at hand. In a series of separates, the grains of a single mineral are often distributed through a series of concentrates rather than in one. This has been a common experience, and is reported in a number of papers.

It soon appeared in the work at Minnesota that there was a relation between the size of grains and the apparent magnetic attraction. The separates of a certain mafic mineral had regularly smaller sizes in the less magnetic separates. On reference to the texts it was found that there is commonly a warning that the material used should be well sized, but evidently screening between two adjoining sieves in the common series, 60, 80, 100 and 200 mesh, does not give well-sized material. Tests were undertaken to see whether operating methods could be improved and to see how widely certain minerals varied in their magnetic behavior.

PRINCIPLES OF MAGNETISM

In a magnetic field, any mineral becomes magnetized by induction of

¹ Hallimond, A. F., An electromagnetic separator for mineral powders: *Mineral. Mag.*, 22, 377-381 (1930).

two poles within each crystal. No mineral is known to be truly non-magnetic, but the magnetic strength and the character of the induced poles vary greatly with different minerals.

According to the familiar law by which magnetic poles of like character repel each other while poles of unlike character attract, minerals may be classified as diamagnetic, paramagnetic, or ferromagnetic. This classification also depends on the pole strengths of the minerals. Diamagnetic minerals are weakly repelled from the field, paramagnetic minerals are weakly attracted to the field, and the ferromagnetics are strongly attracted. Since the only abundant ferromagnetic mineral is magnetite, petrographic separations require splitting the paramagnetic minerals into three groups. These are called "moderately magnetic," "weakly magnetic," and "tailings" products. Diamagnetic minerals also fall into the tailings and for that reason will be largely omitted from the following discussions.

The magnetic strength of the induced poles, or the degree of magnetization, varies in different minerals according to a property called permeability. Permeability is numerically equal to the ratio of total magnetic strength (induced magnetism plus magnetic field) to the strength of the magnetizing field.²

The permeabilities of most ferromagnetic materials are of the order of several hundred, but those of paramagnetic minerals range only slightly higher than one. Since diamagnetic minerals produce an induced field opposite in direction to that of the magnetizing field, their permeabilities are always less than one. The amount of induced magnetism depends also on the strength of the magnetizing field and on the volume of the mineral particle.

Some minerals are known to be magnetically anisotropic, probably due to the crystal structure, though not much work has been done on this property. An example is pyrrhotite, which is practically non-magnetic when the hexagonal axis is oriented in the direction of the magnetizing field, but is ferromagnetic in perpendicular directions.³

When removed from the influence of a magnetic field, the ferromagnetic minerals retain an appreciable part of their magnetism. This part is called permanent magnetism. Probably even paramagnetic minerals also have a small amount of permanent magnetism. Hayes⁴ showed that hematite

² A related property is called susceptibility in many texts. Susceptibility is equal to the ratio of induced magnetic strength to the strength of the magnetic field. Thus the two terms are related but not mathematically equal. The term permeability will be chiefly used in this paper.

³ Coeterier, F., *Naturwissenschaften*, **21**, 251-252 (1933).

⁴ Hayes, E. T., Ferromagnetic properties of hematite; *U. S. B. M., R. I.* **3570**. 25 (June 1941).

retains a small amount of magnetism after being subjected to a very strong field. Although hematite is usually considered to be paramagnetic because of its very low permeability, he states that permanent magnetism is proof of ferromagnetism and suggests that the definition of ferromagnetism be based on this and related phenomena.

A uniform magnetic field is one which is everywhere constant in strength. It usually is part of a larger non-uniform field. A mineral grain in a uniform field will rotate until its poles are oriented with the field, but

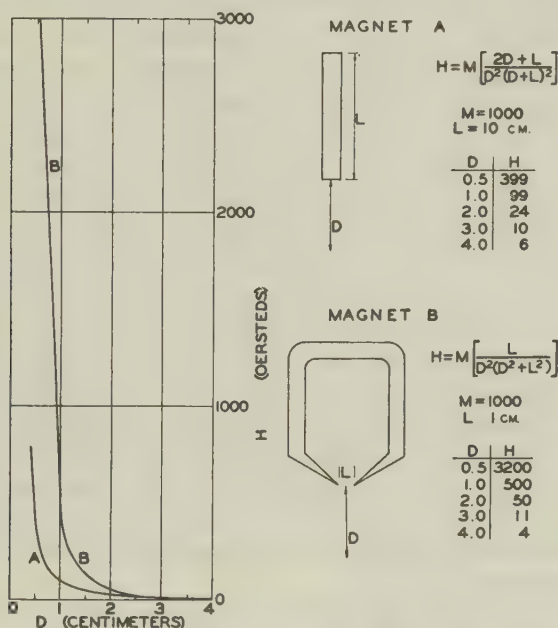


FIG. 1. Comparison of strengths (H) of two magnetic fields at varying distances from the magnets' poles.

the grain will not move to any other part of the field, because the attraction of one pole is offset by the repulsion of the other. This is illustrated by the compass in the earth's field.

Obviously, then, a non-uniform field is required to lift minerals up out of a mixture, but it must have great strength to lift a paramagnetic mineral. Such fields are produced by employing electromagnets having iron cores of various shapes. Figure 1 shows the relative field strengths of two common types of electromagnets at points at different distances from their poles. The magnets have the same magnetic moment but are different in that their poles are different distances apart and have different orientation with respect to the points considered. They show that magnet *B* gives a much stronger field at short distances from the magnet

and also that the strength decreases extremely fast in this region. It should be emphasized that these curves are calculated from ideal point poles and do not show the considerable effect of the shape of the pole pieces.

We know that the force tending to lift a mineral grain from a table to a magnet is greater as the following variables are greater: permeability of the mineral; strength of the magnetizing field at the grain; volume of the grain; and gradient of the magnetizing field at the grain. Also that the force of gravity, tending to hold the grain to the table, is greater as the volume of the grain is greater. From these facts it can be realized that if the product of field strength and field gradient can be made a constant, the force upward will depend on permeability, and a mineral of certain permeability can be rather cleanly separated from others of different permeability regardless of the sizes of grain of ordinary crushed rocks. But, if that product is not constant, tall grains which reach up into the stronger field considerably farther than short grains on the same table, may be picked up, and the short ones will be left even though both sizes have the same permeability. This condition is illustrated by Fig. 2. Stoner⁵ gives the mathematical analysis of these forces and also gives many references which may be helpful in further study of magnetism.

Ideally it is possible to screen the crushed rock into a large number of uniform sizes and change the current for each size so as to get a separation that depends on the nature of the mineral, but in practice this involves too many sizes and too many separations. A powder passing some screen, about 60 to 100 mesh, and washed to remove the fines (by settling 1 inch per minute, for 2 to 5 minutes) gives a range of sizes that is still too great for good separation.

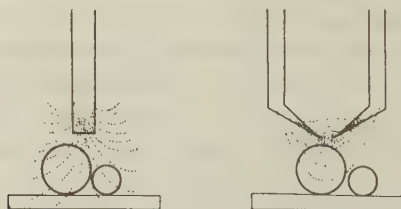


FIG. 2. Field strength and gradient are both greater at the surfaces of the larger grains.

It is possible to design pole pieces in shapes which modify the field to give approximate uniformity in the product of strength and gradient. One pole piece should have a plane surface and the other should be part of a cylinder or sphere. The uniform product of strength and gradient will occur on the axis between them. The dimensions are best determined by

⁵ Stoner, E. C., *Magnetism and Matter*; 35-37, Methuen and Company, London (1934).

trial and error though Fereday⁶ did calculate the proper shapes rather closely using theoretical considerations. Stoner⁷ describes a magnet for which the force was closely uniform along the axis for a distance of 0.8 cm. Fereday's and Stoner's magnets were used for susceptibility or permeability determinations but the one made by Frantz⁸ was used for separating crushed slag and probably also embodied this principle. A disadvantage is that a magnet of this type strong enough to lift paramagnetic minerals would probably be more expensive than other types.

MAGNETIC SEPARATORS

A classification of magnetic separators according to the magnetic phenomena involved has been made by Dean and Davis.⁹ In petrographic work the only type widely used is that based on attraction of particles to a pole of a permanent magnet or a direct current electromagnet. A single electromagnet with adjustable pole pieces may serve as a separator. The minerals are separated from a mixture by placing in a folded paper and moving the paper with a vertical rotary motion between the poles, shifting the paper along until the attracted grains are carried near the end of the paper and can be tipped or brushed out from the rest. More complex separators for petrographic work may be illustrated by that described by Hallimond.¹⁰ In both these instruments, to extract a paramagnetic mineral from a mixture, the powder must be placed within about $\frac{1}{2}$ cm. from the poles where the gradient (Fig. 1) is very large. Consequently they are faulty because they separate large grains from small grains.

PREVIOUS TESTS OF MINERALS

Several petrographers¹¹ have reported some data on the magnetic properties of minerals. Holmes in 1921 concluded that it is not possible to make a detailed list of minerals in order of permeability or attractabil-

⁶ Fereday, R. A., *Proc. Physical Soc., London*; **42**, 251 (1930); **43**, 383 (1931); **46**, 214 (1934).

⁷ Stoner, *op. cit.*, p. 80,

⁸ Dean, R. S., *Annual Report of the Metallurgical Division*, Fiscal Year 1936; *U. S. B. M.*, R. I. **3331**, 45 (Jan. 1937).

⁹ Dean, R. S., and Davis, C. W., *Magnetic concentration of ores: A. I. M. E.*, Milling Volume, **112**, 509-537 (1934). Also, Dean, R. S., and Davis, C. W., *Magnetic Separation of Minerals: U. S. Bureau of Mines*, Bull. **425** (1941).

¹⁰ *Op. cit.* See also an improved Hallimond type mentioned by Evans, *Mineral. Mag.*, **25**, 474-478 (1939).

¹¹ Holmes, A. (From Delesse) *Petrographic Methods and Calculations*, 86 (1921).

Crane, W. R., *Investigation of magnetic fields with reference to ore concentration; Trans. A. I. M. E.*, **31**, 405-446 (1901).

International Critical Tables; VI, p. 364, McGraw-Hill Book Co. (1929).

Tyndall, J., *Diamagnetism and Magne-crystallic Action*, D. Appleton and Co. (1888).

ity however measured that would be generally applicable. It seems likely that this is so because most rock minerals are isomorphous mixtures and there is commonly a wide range in composition, not only in different crystals but even in different zones in a single crystal. While the differences in data recorded by the several authors can be so explained, there is little to indicate how far the magnetic attractability ranges in a single series. Tyndall¹² showed that pure lime carbonate is diamagnetic but that an isomorphous mixture of lime and iron carbonate is paramagnetic. Probably the minerals in which Fe and Mg compounds form isomorphous series will show a wide range. Several have been selected to test the ideas stated in this discussion, but the work has not been done with pole pieces properly designed to give only differences in permeability.

EXPERIMENTS

A separator modelled after that of Hallimond¹³ was used with constant adjustment of pole pieces and platform. The feed was satisfactory only for grains smaller than 40 mesh.

Experiment 1. A two inch fragment taken from one side of a six inch crystal of black tourmaline was crushed and screened to yield five grades. None of the material was picked up by the first magnet but the other two magnets attracted some from each size grade and left some in the tailings from each (Table 1 and Fig. 3).

TABLE 1. MAGNETIC SEPARATION OF CRUSHED TOURMALINE

Mesh	Caught by 2nd magnet	By 3rd magnet	Tailings
30-40	80.0%	17.5%	2.5%
40-60	70.0	25.0	5.0
60-80	52.5	35.0	12.5
80-100	49.0	38.0	13.0
100-200	17.0	58.0	25.0

Clearly the supposedly uniform mineral is distributed in three separates regardless of size, and clearly the coarser grade sizes are more largely concentrated by the weaker magnet, and the finer sizes more largely by the strongest magnet and in the tailings.¹⁴

¹² Tyndall, *op. cit.*

¹³ Hallimond, *op. cit.*

¹⁴ Dean, R. S., and Davis, C. W., *op. cit.*

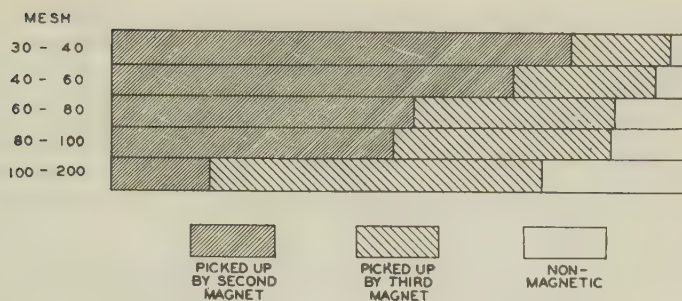


FIG. 3. Magnetic separation of crushed tourmaline.

The next experiment (Experiment 2, below) confirmed the conclusions of this in every way but only two sizes were used, 40-60, and 80-100. In each case the finer material seemed to be less magnetic, but the differences should probably be attributed wholly to the design of the magnets. Data for these minerals are not here listed as they simply support the conclusion drawn from tourmaline.

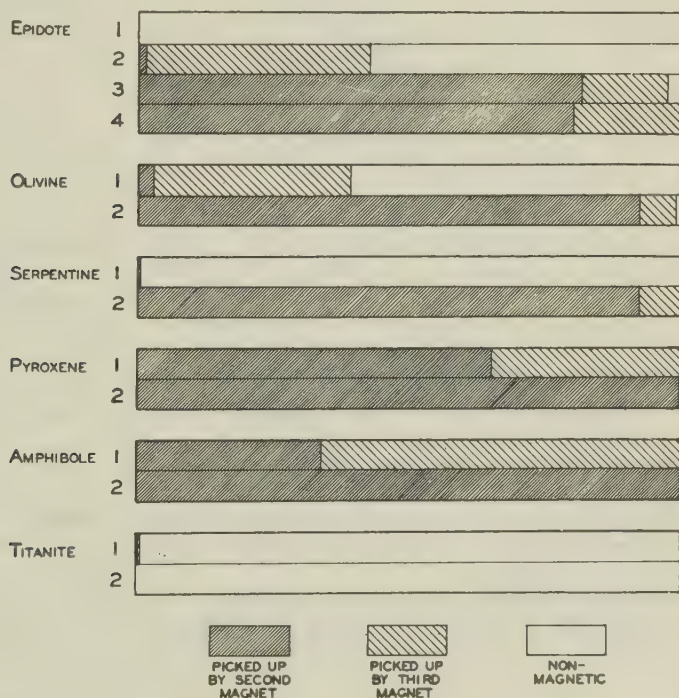


FIG. 4. Magnetic separates of several minerals.

Experiment 2. Several minerals forming isomorphous series from Mg to Fe extremes were tested at 80 to 100 mesh sizing to show how differently the ferruginous and magnesian varieties behave in a magnetic separator of the Hallimond type. Grains ranged from 0.140 to 0.173 mm. in diameter. Samples were those that happened to be available in the Department of Geology at the University of Minnesota. A correction was made for any impurity found by microscopic examination of the sized material. None of the minerals yielded any separate to the first magnet, which is intended to take out the ferromagnetic minerals. Table 2 and Fig. 4 show the distribution through the rest of the separator.

TABLE 2. MAGNETIC SEPARATES OF SEVERAL MINERALS

		Magnet 1	Magnet 2	Magnet 3	Tailings
Epidote	1	none	0	0	100
	2	"	1.1	40.8	58.1
	3	"	81.4	15.8	2.8
	4	"	79.8	20.2	0
Olivine	1	"	2.7	36.0	61.3
	2	"	91.8	6.9	1.2
Serpentine	1	"	0	0.2	99.8
	2	"	92.0	8.0	0
Pyroxene	1	"	64.5	35.5	0
	2	"	99.6	0.4	0
Amphibole	1	"	33.6	66.4	0
	2	"	100.0	0	0
Titanite	1	"	0.3	0.3	99.4
	2	"	0	0	100.0

Epidote group. Specimen 1, zoisite, east of Rainy Lake, Ontario. Specimen 2, green, fibrous, from pegmatite at Dewey, Montana. Specimen 3, dark green, from Ute Creek, Colorado. Specimen 4, very dark, from Sulzer, Alaska.

Olivine group. Specimen 1, light green, Carolina. Specimen 2, dark gray-green, Mooihoek, Bushveld.

Serpentine group. Specimen 1, green, and 2, dark green; localities unknown.

Pyroxene group. Specimen 1, diopside, light gray-green, Ariege, France. Specimen 2, augite, black, Hybla, Ontario.

Amphibole group. Specimen 1, actinolite, and 2, hornblende; localities unknown.

Titanite. Specimen 1, medium brown, unknown locality. Specimen 2, dark brown, Westport, Ontario.

The magnetism of titanite was investigated because it has been supposed to show marked variability.¹⁵ The differences in color do not seem related to such a variability. No magnetic samples are available here except some in which magnetism results from opaque inclusions.

SUMMARY

This paper covers two points, namely, that with most magnets used in petrographic or mineral separations, the material must be accurately sized, but that the difficulty might be overcome by a different design of the pole pieces; and that, in an isomorphous series grading from an Mg compound to an Fe compound, the Fe compound is much more strongly attracted as might be expected, and in zoned crystals a clean magnetic separation of that mineral from another is hardly to be expected.

¹⁵ Tyler and Marsden, Report of Committee on Accessory Minerals: *Div. of Geol. and Geog., Nat. Research Council* for 1936-7, p. 13.

ZOISITE-PREHNITE ALTERATION OF GABBRO*

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ABSTRACT

Metagabbro in the vicinity of Baie Verte, Newfoundland, has been altered to an aggregate of zoisite and prehnite. Microscopic study shows zoisite intimately penetrated by a network of prehnite veinlets. Chemical analyses indicate a large increase in lime and decrease in silica, iron, magnesium and alkali content. The alteration is attributed to hydrothermal solutions probably related to the nearby granitic rocks.

INTRODUCTION

Baie Verte is an indentation in the large peninsula situated between White Bay and Notre Dame Bay on the northern coast of Newfoundland

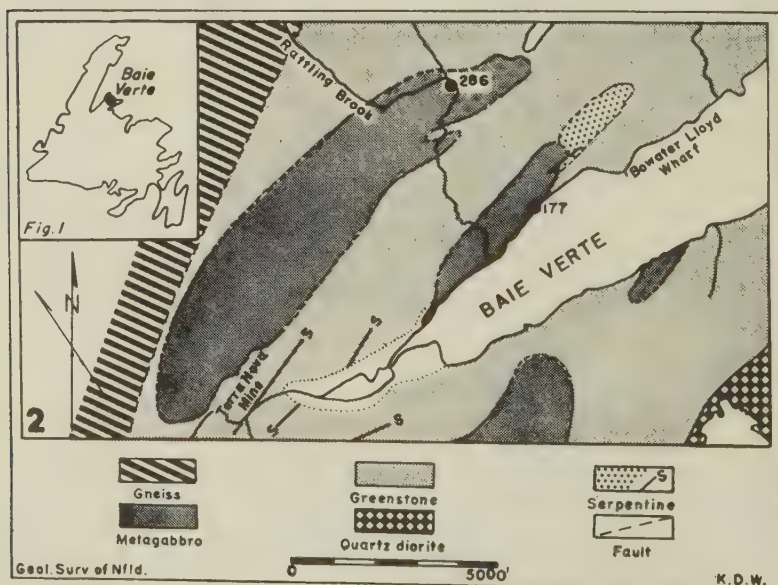


FIG. 1. Map of Newfoundland showing position of Baie Verte.

FIG. 2. Geological map of southwestern part of Baie Verte.

(Fig. 1). In the vicinity of the bay, a thick, highly folded section of rocks consisting principally of greenstones has been intruded by large, dominantly concordant bodies of ultramafics and gabbro (11).

The ultramafics have undergone serpentinization and steatitization.

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The gabbro has suffered saussuritization, uralitization, silicification, carbonatization and locally, alteration to a zoisite-prehnite assemblage. Large masses of quartz diorite and granite have intruded and metamorphosed the other rocks of the area.

METAGABBRO

The metagabbro is composed principally of saussuritized plagioclase and uralitized pyroxene in varying proportions. For the most part, it is a light greenish-gray, medium grained, massive rock although local phases are highly sheared and, therefore, difficult to distinguish from the greenstone of the area. Irregular masses of a pegmatitic facies, ranging from a fraction of an inch to several feet in thickness, are of common occurrence within the large bodies.

None of the thin sections which were examined showed unaltered plagioclase and a relatively small proportion of them contained any unaltered pyroxene. A study of fresh-appearing specimens from the intrusive to the northwest of the Terra Nova mine (Fig. 2), revealed that the pyroxene, occurring as anhedral grains averaging about 0.25 mm. in diameter is augite (7, p. 520) with the following diagnostic optical properties: $2V = 47\frac{1}{2}^\circ$, $N_p = 1.690$, $N_g = 1.718 \pm .003$; $(En_{40}Fs_{20}Wo_{40})$.¹ Many of the grains are twinned. Most of the augite shows a peripheral alteration to actinolite or colorless tremolite. Some, however, are altered to actinolitic hornblende characterized by a fairly deep green color and distinctive pleochroism.

Plagioclase occurs as irregular polysynthetically-twinned laths, 0.75 mm. in average length, which are highly altered. They consist of albite throughout which numerous small prisms of clinozoisite and grains of epidote are disseminated. Clinozoisite also occurs as clusters of euhedral prisms in areas interstitial to the plagioclase laths. Leucoxene is present in abundance as pseudomorphs of subhedral skeletal crystals of ilmenite about 0.3 mm. in diameter.

A specimen of massive rock consisting of saussuritized plagioclase and partially altered pyroxene (Fig. 3, Plate I) from the southwest shore of Baie Verte, 2300 feet south of the Bowater Lloyd Company's wharf (Fig. 2), gave the following analysis (Table 1). Although the minerals are highly altered, the texture of the rock is well preserved and the following proportions were determined by Rosiwal analysis:

MODE

Altered plagioclase	53% by weight
Pyroxene and altered pyroxene	47% by weight

The specific gravity and porosity of the analyzed rock were determined as 3.01 and 0.3 per cent, respectively.

¹ Hess, H. H., Oral communication (cf. 7, Fig. 10, p. 585).

TABLE 1

METAGABBRO No. 177				ZOISITE-PREHNITE No. 286	
Chemical Analysis		Norm		Chemical Analysis	
SiO ₂	48.74	Or.	0.56	SiO ₂	44.15
Al ₂ O ₃	18.26	Ab.	15.72	Al ₂ O ₃	19.07
Fe ₂ O ₃	1.23	An.	41.14	Fe ₂ O ₃	1.03
		Ab ₃₀ An ₇₀			
FeO	4.08	En.	8.90	FeO	2.49
MgO	8.76	Fs.	2.64	MgO	5.37
CaO	14.40	Wo.	12.64	CaO	25.22
		24.18 Di.			
Na ₂ O	1.87	En.	5.43	Na ₂ O	.14
K ₂ O	.10	Fs.	1.54	K ₂ O	.00
H ₂ O+	2.25	Fo.	5.30	H ₂ O+	2.46
H ₂ O-	.02	Fa.	1.66	H ₂ O-	.03
		6.97 Hy.			
		6.96 Ol.			
CO ₂	.05	Mt.	1.86	CO ₂	.03
TiO ₂	.18	Ilm.	0.30	TiO ₂	.14
P ₂ O ₅	.01	H ₂ O+	2.25	P ₂ O ₅	.02
MnO	.10	H ₂ O-	.02	MnO	.08
Total	100.05	Total	100.06	Total	100.23

Analyses by G. Kahan.

	METAGABBRO 177		ZOISITE-PREHNITE 286	
Mode	Altered plagioclase	53%	Zoisite	83%
	Pyroxene and alterations	47%	Prehnite	15%
			Actinolite	2%
Specific Gravity	3.01		3.18	
Porosity	0.3 %		0.1 %	

ZOISITE-PREHNITE ALTERATION

Near the northern end of the sill-like body of metagabbro which extends from the vicinity of the Terra Nova mine to a short distance beyond Rattling Brook (Fig. 2), the rock has been altered to an aggregate consisting principally of zoisite and prehnite. The zoisite-prehnite rock is white or faintly greenish in color, due to the presence of actinolite and varies in grain size from extremely fine to fairly coarse. Although outcrops are not abundant, it appears that the alteration extends over an area of several hundred square feet and grades into the normal metagabbro.

Under the microscope it is seen that the zoisite ($N_p = 1.695 \pm$, $N_g = 1.710$; positive elongation; $2V = 50^\circ \pm$) is intimately penetrated by an intricate network of minute prehnite ($N_p = 1.617$, $N_g = 1.645$; positive elongation; $2V = 65^\circ \pm$) veinlets (Fig. 4, Plate I). The zoisite, characterized by dark gray or anomalous deep blue interference colors, is readily distinguishable from the prehnite because of its higher relief and lower birefringence. In many places, it shows a common orientation over areas 1 to 2 mm. in diameter. A few of the grains show poor polysynthetic twinning. Commonly there is a distinct variation in the interference color within an individual crystal of zoisite. This has been interpreted by Winchell (12, p. 311) as the result of a variable Fe_2O_3 content. According to Rogers and Kerr (10, p. 320) the anomalous deep blue interference color is characteristic of the non-ferrian variety of zoisite.

Winchell (12, p. 430) has presented data which show that the indices of refraction of prehnite increase and the birefringence decreases with progressive replacement of Al_2O_3 by Fe_2O_3 . The indices of the prehnite examined by the writer correspond very closely to those given by Laitakari (12, p. 430. $N_p = 1.615$, $N_m = 1.624$, $N_g = 1.645$) for prehnite with a Fe_2O_3 content of 0.95%.

Some of the sections are traversed by veinlets consisting of euhedral and subhedral zoisite crystals projecting from the borders into a central portion filled with prehnite (Fig. 5, Plate I). Many of the zoisite crystals of the veinlets have been fractured and replaced by prehnite. Other veinlets consist of transversely arranged lamellar grains and plumose aggregates of prehnite (Fig. 6, Plate I).

Zoisite-prehnite rock from the south bank of Rattling Brook at a point 4600 feet N. 15° W. from its mouth (Fig. 2), was analyzed with the results given in Table 1. The mode of the analyzed rock is as follows:

Zoisite = 83% by weight
Prehnite = 15% by weight
Actinolite = 2% by weight

The specific gravity and porosity of the rock are 3.18 and 0.1%, respectively.

SIMILAR OCCURRENCES

The saussuritization of plagioclase and uralitization of pyroxene in gabbroic rocks is very common (9, pp. 210-214). Harker (6, p. 174) who attributes these alterations to deuteric action, states that the usual lime-aluminosilicates in saussurite are zoisite and epidote, but that prehnite is also found. In discussing metasomatism, however, he attributes the extreme prehnitization of various lime-aluminosilicates to the action of heated water of magmatic origin.

"In some localities, always in the near neighbourhood of a plutonic contact, this destructive action has been carried far, even in the extreme case to the reduction of the whole rock to an aggregate essentially of prehnite and quartz. Any lime-felspar present is first converted" (6, p. 134).

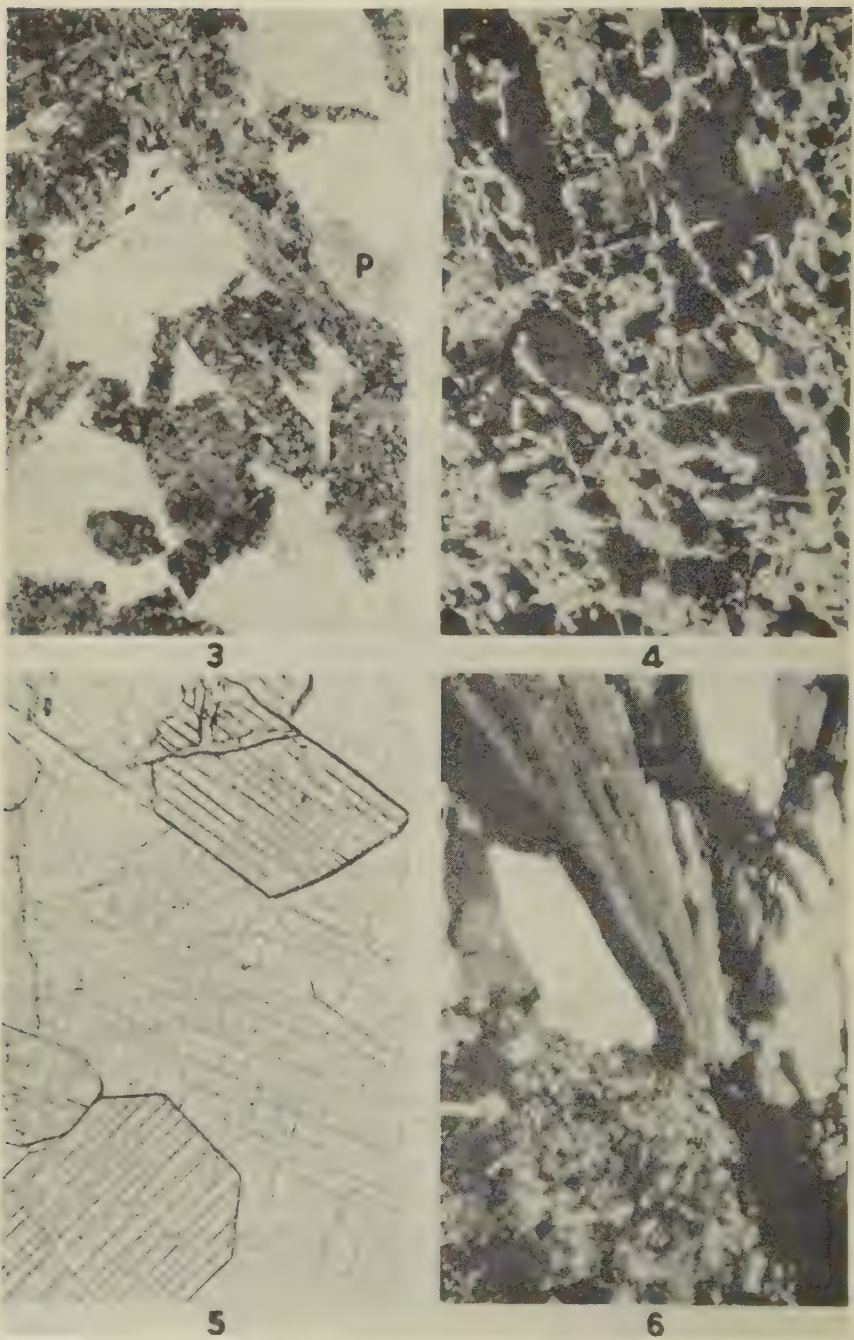


PLATE I

Benson (1, pp. 682–688) has described the occurrence of prehnite and zoisite in the altered eucrites of the Great Serpentine Belt of New South Wales. The usual altered rock consists of

“dusty diallage more or less completely changed to tremolite, and dull grey-white saussurite traversed by small veins of clinozoisite. . . . Occasionally, the saussurite would be flaked with lighter spaces, which consist of optically continuous prehnite” (1, p. 684).

At one locality, the feldspar has been entirely altered to coarsely granular zoisite. Another modification is characterized by the presence of abundant prehnite.

“This striking mineral forms in veins; the individual grains are rarely as much as 1 mm. in diameter. . . . The saussurite, on either side, is seen to have passed almost entirely into a fine mosaic of prehnite grains. The diallage in this rock is being altered, partly to tremolite, but chiefly to antigorite and pale pink garnet” (1, pp. 684–685).

Flett and Hill (5) have discussed the occurrence and origin of prehnite in the altered gabbro associated with the serpentine of the Lizard area. The saussurite alteration of the primary labradorite

“where more coarsely crystalline than usual . . . can be ascertained to contain certain minerals such as prehnite, garnet, zoisite, chlorite and alkali feldspar mixed with a variable amount of actinolite. Prehnite is very frequent, and in some cases occurs in masses and nodules several inches in diameter.”

The writers attribute the alteration to the action of solutions, derived from the granitic gneisses of the area, after percolating through the serpentine.

Cooper (4) has also observed that “proximity to serpentine has favored the prehnite type of alteration” (4, p. 34) in the gabbroic rocks of the southern part of the Bay of Islands complex of western Newfoundland. In one area, the feldspars of anorthositic gabbros and troctolites which are interbanded with serpentinized dunite are completely altered to saussurite containing thick veins and blebs of prehnite.

FIG. 3. Photomicrograph of metagabbro showing saussuritized plagioclase (dark) and highly uralitized pyroxene. (Relict pyroxene (p) high relief.) Magnification: 40X.

FIG. 4. Zoisite (dark) partially replaced by prehnite (light). Magnification: 120X. Crossed nicols.

FIG. 5. Crystals of zoisite (high relief) projecting from borders of veinlet into central filling of prehnite. Note replacement of zoisite by prehnite. Magnification: 120X.

FIG. 6. Transversely arranged prehnite grains in veinlet. Magnification: 120X. Crossed nicols.

"Unquestionably the original rock was an anorthositic gabbro or troctolite. What then has caused the extreme saussurite-prehnite alteration here? Regional metamorphism, elsewhere in the region, has produced an amphibole or chlorite type of alteration with only rarely a little prehnite and some zeolite veins. The latter are probably always late-phase, low or intermediate temperature, hydrothermal effects since they are controlled by distinct fractures in the rocks which cross the other minerals. Only in the thin anorthosite bands in feldspathic dunite is prehnite quantitatively important. Apparently proximity to serpentine has favored the prehnite type of alteration" (4, p. 34).

However, prehnite may be formed in areas in which the hydrothermal solutions have not been affected by the presence of serpentine. Buddington (2, 3) has recently described the saussuritization and prehnitization of anorthositic rocks in the eastern Adirondacks. At one locality the plagioclase of several thin sheets of gabbroic anorthosite has been almost entirely replaced by a granular white prehnite which occurs as fine fibrous to lamellar aggregates and as terminated crystals projecting into druse fillings of quartz or of quartz and prehnite.

"The local saussuritization and prehnite replacement of the anorthositic rocks is later than the deformation of the rocks and may be a product of late-stage solutions originating in the granitic magmas" (2, p. 178).

CONCLUSIONS

A comparison of the composition of the typical metagabbro with that of the zoisite-prehnite rock given in Table 1 shows that the principal change involved in the formation of the latter was the addition of lime. Decrease in the silica, iron, magnesium and alkali content is also noticeable.

The saussuritization of the plagioclase and the uralitization of the pyroxene to form the typical metagabbro is probably the result of both deuteric action and regional metamorphism.

The alteration of the serpentinized ultramafics in the area to talc-carbonate rock is believed to be attributable to the presence of hydrothermal solutions probably related to the nearby granitic rocks (8, p. 643). It seems probable that somewhat similar hydrothermal solutions from the same source could alter the metagabbro to the zoisite-prehnite rock and to a zoisite-quartz assemblage which occurs elsewhere in the same region. During the alteration, a change in conditions resulted in the replacement of zoisite by prehnite, a mineral richer in silica and water.

ACKNOWLEDGMENTS

The field work upon which this paper is based was carried out during the summers of 1938 and 1939 while the writer was employed by the Geo-

logical Survey of Newfoundland. A large portion of the laboratory expenses was borne by the Department of Geology of Princeton University.

Professor H. H. Hess gave the writer considerable aid in the optical work. The writer also wishes to thank Professor A. K. Snelgrove for help in the field, and Professor A. F. Buddington for advice and criticism in the preparation of the manuscript.

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NOTES AND NEWS

IDIOMORPHIC CORDIERITE FROM SAFE HARBOR, PENNSYLVANIA

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Springfield, Pennsylvania.

In the examination of altered schists from the quarry at Safe Harbor, Pa., the author found small idiomorphic crystals of cordierite in association with other aureolitic minerals. These cordierite crystals are quite abundant forming in some instances as much as 25% of the rock. As far as the author is aware, idiomorphic cordierite has not been reported from Pennsylvania, and it is the purpose of this note to place this locality on record.

A distinction should be drawn between occurrences of cordierite of this type and occurrences of coarse, granular cordierite as found in granitic gneisses. The latter are a feature of deep seated alteration, usually extending over wide areas. The former are the result of thermal conditions which affect the stability of the micas and other aluminum minerals and are usually confined to narrow contact aureoles.

The cordierite at Safe Harbor occurs in a brecciated zone in a highly micaceous schist. This schist lies on the opposite side of the Antietam quartzite from the Vintage dolomite, and according to the recorded series should be the Harpers formation. The brecciated zone crosses the quarry in a N.E.-S.W. direction, roughly parallel to the structure of the schist. As the thickness of the Cambrian sediments varies greatly in this area it is quite possible that this brecciated zone is near the unconformity at the base of the Cambrian. This zone was intruded presumably during Paleozoic time by a granitic derivative which enveloped fragments of the schist. There does not appear to be any direct connection between this granitic intrusive and the aureolitic minerals although some of the fragments contained in the granite show aureolitic alteration. During Triassic time the area was fissured in a N.-S. direction. These fissures were intruded by a basaltic magma which formed the main diabase dike 50 ft. wide and many smaller parallel dikes of diabase and basaltic glass. These Triassic dikes cut directly across both the brecciated zone and the schists. The aureolitic minerals are found at the intersection of the dike and the brecciated zone.

The presence of numerous dikelets of basaltic glass suggests that a large body of basaltic magma has been intruded somewhere in the vicinity of the intersection causing the thermal conditions that developed the aureolitic minerals.

Since the schistose structure is retained in much of the aureolitic rock, it is evident that the stress minerals were formed before either the brecciation or thermal alteration took place. The development and metamorphism of the schists of this area have been very carefully traced and described as far as the almandine-staurolite-cyanite stage, both by Dr. Eleanor B. Knopf and Dr. Anna I. Jonas in *U.S.G.S. Bull.* **799** (1929), and by Dr. Ernst Cloos and Dr. Anna Hietanan in *G.S.A. Special Paper* **35** (1941). The aureolitic stage of alteration, however, has not been described or reported from the area.

Following the formation of the schist minerals, as described in these papers, the relations of the igneous rocks to each other and to the schist inclusions would indicate the following sequence. Subsequent to the formation of the schist minerals and relief of stress conditions, came the E.-W. brecciation with accompanying granitic intrusion and tourmalinization of the schist. All the minerals formed during this period are characteristically coarse grained. The minerals formed at this time appear to have remained stable until the Triassic period.

During Triassic time came the N.-S. fissuring accompanied by the intrusion of a mass of basaltic magma. This intrusion created thermal conditions which altered both the schist and the granite in the brecciated zone. The micas of the schist were unstable under the conditions imposed and broke down forming the aureolitic minerals, orthoclase, cordierite, a second generation of biotite, hercynite, rutile and sillimanite. This alteration of the micas can be seen in all stages from slightly altered schist to the aureolitic rock. The minerals formed during this period are characteristically very fine grained. They represent an adjustment to changed thermal conditions without change in the chemical composition of the rock.

As the basaltic magma cooled there came a period of hydrothermal activity. Solutions from the intrusive following channels through the brecciated zone and along the structure of the schists formed albitic veinlets. These hydrothermal solutions dissolved and reacted with the minerals of the rocks they passed through forming crystal-lined vugs. The characteristic minerals are albite, albite-quartz intergrowths, chlorite, calcite, sphene and pyrite. The minerals of this period are moderately coarse grained. This final hydrothermal alteration is distinctly superimposed on the aureolitic alterations although in places it blends into the aureolitic rock.

The cordierite crystals with which this note is concerned are small in size, generally ranging between .002 and .004 mm. across the prism face. A few are a little larger. Untwinned crystals are of simple form bounded by pinacoids, the prism and the *d* faces. Pseudohexagonal crystals with

the prism face as the twinning plane are common (Fig. 1), and some crystals show polysynthetic twinning with pseudo-hexagonal outline (Fig. 2). The crystals are very unstable and alter readily, some to pinnite, some to chlorophyllite. The pinnite alteration produces a fine grained matte of mica. The chlorophyllite alteration is a pseudomorphous alteration, a pseudo-hexagonal twin of chlorophyllite replacing a pseudo-hexagonal twin of cordierite.

Most of the material available is in an advanced stage of alteration so that it was impossible to separate fresh material for index determination

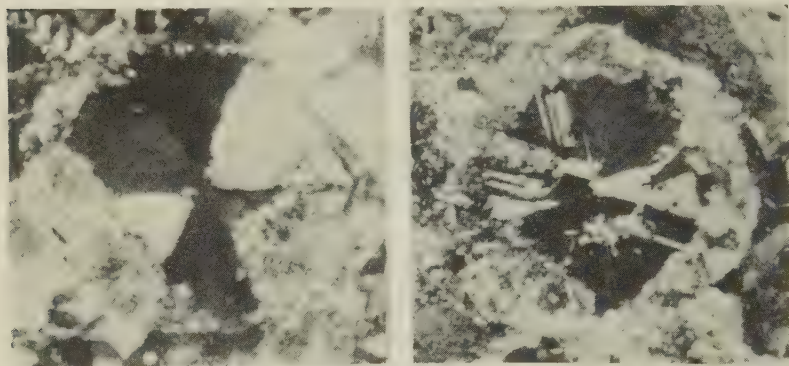


FIG. 1. Basal section of pseudo-hexagonal crystal due to penetration twins. Bounded by six brachypinacoids. Twin-plane is $\{110\}$. Alteration to pinnite starting along outer edge. Crossed nicols. \times about 140 diameters.

FIG. 2. Polysynthetic twinning with pseudo-hexagonal outline. Alteration as in Fig. 1. Crossed nicols. \times about 140 diameters.

or for a chemical analysis. However, a minute fragment from a thin section gave 1.552 for γ and 1.545 for α . Basal sections of unaltered crystals give a poor interference figure showing the emergence of a negative bisectrix with an optic angle between 60 and 65° .

These idiomorphic crystals have formed in contact with orthoclase which according to Harker is the only mineral with weaker crystal assertiveness than cordierite, and the only mineral against which cordierite will assume its own crystal form.

Much work still remains to be done in this area before the extent of this aureole can be established or the source of the thermal conditions definitely established.

AN UNUSUAL ASYMMETRICALLY BANDED FISSURE VEIN;
A DISCUSSION¹

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It is unfortunate that a theory of vein formation so in conflict with known facts of physical chemistry should be based on one small specimen, especially when the orientation of the specimen is not known, but must be assumed to be such as to accord with the theory. There is hardly a sentence in the interpretive part of the paper that is not open to question. In the following discussion no attempt is made to select all of the things that could be questioned; only those points are picked out that are answerable on general grounds, without reference to details of the specimen. Shaub makes an attempt at justification on the grounds that insufficient experimental work has been done to prove or disprove the operation of immiscible concentrated solution pairs. As a matter of fact, there is ample experimental evidence to indicate that such immiscible solutions do not exist at the temperatures under which such vein deposits form. The mineral assemblages give a reasonably accurate estimate of the temperatures of formation; at least, they indicate a temperature above which the solutions could not have been when crystallization began. Estimates range from 575° C. down.

According to Shaub's description of the vein under discussion, the material, if it crystallized in situ, would have had to consist almost entirely of SiO_2 , FeO , PbS , and CO_2 , because all the minerals are anhydrous and there are few voids that might have contained water left from the crystallizing solutions. Yet the temperature must have been quite low. This is indicated not only by the mineral assemblage (FeCO_3 and SiO_2 in solution at high temperature and pressure with little or no water present would produce iron silicate and not siderite and quartz), but also by the form of the quartz. The quartz, from its elongate prismatic form as shown in the photomicrographs, must be the low temperature form and was, therefore, formed below 575°, although it was, according to Shaub, the first mineral to crystallize.

If the layers suggested had separated as liquids there would have been three layers, because the "lower" layer of lead sulfide and silica would have formed two immiscible liquids. Moreover, the temperature required to keep these materials molten probably would have melted the wall rock, yet the photographs show no sign of melting adjacent to the veins.

It has been suggested by Farmin that carbon dioxide might aid in keeping such concentrated solutions (ore magmas) fluid at lower tempera-

¹ Shaub, B. M., *Am. Mineral.*, **27**, 507-516 (1942).

tures, but recent experimental work done at the Geophysical Laboratory indicates that the effect of carbon dioxide is in the opposite direction, forcing silica out of solution, thus making the solution more dilute rather than more concentrated.

In a previous paper² Shaub cites observations by Newhouse in support of the view that some ore-forming solutions may have been concentrated. Newhouse did find some solutions in liquid inclusions that were relatively concentrated ($15\% \pm$), but this concentration was of soluble salts such as NaCl, which says nothing of the concentration of SiO_2 or PbS in an ore-forming solution.

Greig³ has shown that immiscibility almost certainly has no part in the formation of igneous rocks. It is even less likely that it plays a part in vein formation, because as the temperature decreases and the water content increases, immiscibility becomes less and less probable. The analogy of slags and mattes (p. 154) does not hold, not only because of differences in composition, but also because the temperatures cannot have been high enough.

Study of the pictures indicates that a straightforward interpretation on the basis of a homogeneous dilute solution, and replacement, can probably explain all the features, but to put forth a definite hypothesis merely from inspection of a few photographs is hardly justified.

The questions proposed on pages 513-514 are largely academic. A careful study of the specimen would be required to answer them specifically, but some of them become pointless at once if deposition from dilute solution is assumed rather than replacement (3, 5, 8). Question 4 is based on the assumption that FeCO_3 is "much more soluble" than quartz. That all depends upon the solution doing the dissolving. It is easy to prepare a solution in which quartz is much more soluble than FeCO_3 , and similar solutions may well have a part in vein deposition.

Each step in the process of development as outlined by Shaub (pp. 515-516) is open to discussion:

(1) The development of immiscible liquids in silicate systems during cooling and crystallization can occur. However, in all systems containing compositions even remotely resembling magmas in which immiscibility occurs, it can be developed only at very high temperatures and from mixtures that approach 100% SiO_2 , by the crystallization of silica.

(2) Having the liquids come in as a heterogeneous mixture of globules is obviously merely a convenient hypothetical mechanism for getting both of them into a small fissure simultaneously. Actually, if two such liquids had not separated at the higher temperatures obtaining before their intrusion, it is inconceivable that they would separate into perfect

² Shaub, B. M., The cause of banding in fissure veins: *Am. Mineral.* **19**, 393-402 (1934).

³ Greig, J. W., Immiscibility in silicate melts; *Am. Jour. Sci.*, **13** (5), 1-44 and 133-154 (1927).

layers on cooling and crystallization. The form of at least some of the globules would almost certainly be preserved.

(3) There is no evidence at all for gravity separation by settling of the liquid containing PbS, because the orientation of the specimen is assumed; it was not even known approximately.

(4) Crystallization may not begin at an interface between immiscible liquids in a crucible, because the melt cools from the sides and bottom but where the rate of cooling is uniform throughout a given volume, crystallization is more likely to begin at a discontinuity like an interface than within either liquid. This tendency is clearly shown in a photomicrograph by Greig⁴ which shows crystals forming a ring at the interface around a globule, the center of which did not crystallize at all.

(4, 5, & 6) The order of crystallization is described so as to fit the theory, but there are inconsistencies (See 7).

(7) Separation of a *liquid phase* of quartz to crystallize alone in the middle of the vein is unthinkable. Even if water is concentrated along with it to keep it in solution (which possibility is not mentioned) there are two inconsistencies: In the first place, in (6) siderite, not quartz is said to be the last to crystallize. In the second place, the pictures (especially Fig. 5) show this last quartz to crystallize to be indistinguishable from that of the galena-quartz layer, which would hardly be expected if they crystallized at different times, presumably at different temperatures, and from solutions of quite different compositions.

Banding in the large vein is cited as an example of rhythmic fractional crystallization,⁵ which is another process that cannot take place. When a cooling solution becomes saturated with respect to a solid phase and crystallization of that phase begins it continues to crystallize until it has all precipitated, or it becomes unstable, or there is a change of conditions that renders the solution unsaturated or just saturated again. Shaub does not recognize any of these factors, but assumes that a phase may crystallize for a time, then stop while another one crystallizes, then precipitate again, during continuous cooling of a stagnant solution. This is a convenient mechanism for producing banding, but it is hardly in accord with the way solutions are known to behave.

(8) Well defined bands are no evidence of solutions at rest. Much better defined bands than the ones pictured are formed in boilers and steam pipes through which dilute solutions are moving at high speeds and with much turbulence.

The evidence from the pictures, coupled with experimental data, indicates that such a vein could not have formed from "concentrated immiscible mineral solutions."

⁴ *Op. cit.*, Fig. 6a.

⁵ Shaub, *op. cit.*, pp. 398-399.

FELLOWSHIPS AVAILABLE IN MINERALOGY
AND STRUCTURAL CRYSTALLOGRAPHY

Two fellowships are available in the Department of Geology, Massachusetts Institute of Technology, in the fields of Mineralogy and Structural Crystallography. One of these, a teaching fellowship, carries a stipend of \$500 per academic year plus free tuition. Up to eighteen hours per week may be required of the holder of this fellowship. The duties consist of teaching and other assistance in connection with laboratory instruction in mineralogy and possibly optical crystallography. Preference will be given to a student specializing in mineralogy or crystallography.

Another fellowship, concerned chiefly with carrying out investigations in structural crystallography and allied fields, requires an investigator with a fairly good background in crystallography and preferably having had some experience in the x -ray study of crystal structures. This fellowship, which is of a more permanent nature, requires the full time of the incumbent and carries a stipend of about \$2000.

Anyone interested in either of these fellowships should communicate with Professor M. J. Buerger, Department of Geology, Massachusetts Institute of Technology, Cambridge, Massachusetts, giving full details regarding their qualifications.

NOMINATIONS FOR OFFICERS OF THE MINERALOGICAL
SOCIETY OF AMERICA FOR 1943

The Council has nominated the following for officers of the Mineralogical Society of America for the year 1943:

PRESIDENT: J. Frank Schairer, Geophysical Laboratory, Washington, D. C.

VICE-PRESIDENT: John W. Gruner, University of Minnesota, Minneapolis, Minnesota.

SECRETARY: Paul F. Kerr, Columbia University, New York, N. Y.

TREASURER: Earl Ingerson, Geophysical Laboratory, Washington, D. C.

EDITOR: Walter F. Hunt, University of Michigan, Ann Arbor, Michigan.

COUNCILOR (1943-1946): C. S. Hurlbut, Jr., Harvard University, Cambridge, Massachusetts.

ANNOUNCEMENT OF ANNUAL MEETING

The twenty-third annual meeting of the society will be held in Ottawa, Canada, December 29-31, 1942, in connection with the 54th meeting of the Geological Society of America.

Members of the society who are planning to present papers at the scientific sessions of the annual meeting should notify the secretary as soon as possible in order to receive the proper blanks for their abstracts. All abstracts should be in the secretary's office by *November 1*.

Final announcement of the annual meeting will be distributed to members of the society, along with the ballot for officers, the middle of October. The final program of the meeting, including the schedule of papers, abstracts, and other information will be sent to each member in December. Further specific information regarding the annual meeting may be obtained from the secretary's office.

PAUL F. KERR, *Secretary*

DISCREDITED SPECIES

Ochrolite = Nadorite

L. G. SILLÉN AND L. MELANDER: X-ray studies on the oxyhalide minerals nadorite (ochrolite) (PbSbO_2Cl) and ecdemite. *Zeits. Krist.*, **103**, 420-430 (1941); through *Chemical Abstracts*, **36**, 1872 (1942).

X-ray study shows that ochrolite is identical with nadorite.

MICHAEL FLEISCHER

Sterrettite = Eggonite

F. A. BANNISTER: The identity of 'eggonite' with sterrettite. *Mineral. Mag.*, **26**, 131-133 (1941).

Comparison of x-ray, optical and chemical data shows that eggonite (from Felsöbanya?) and sterrettite from Fairfield, Utah, are identical. It is suggested that the name eggonite be dropped.

DISCUSSION: The name eggonite was given in 1879 by Schrauf to crystals he found on crystallized hemimorphite in compact smithsonite from Altenberg, Belgium. Schrauf believed the mineral to be a cadmium silicate and gave the name (from the Greek meaning "a grandson") because he thought it to be the third generation in the series of zinc-cadmium minerals. In 1929 Krenner found that the material was really a hydrous aluminum phosphate, and that the crystals had been artificially attached to the specimen. He believed that Felsöbanya was the correct locality. According to the rules of priority, Krenner would have been justified in giving a new name to the mineral, but he did not do so. Eggonite is listed in both Dana-Ford and Larsen-Berman as a hydrous aluminum phosphate and the optical data given are correct. It would seem, therefore, to be a violation of the generally accepted rules of priority to drop the name eggonite for sterrettite (E. S. Larsen, 3rd, and A. Montgomery, 1940). Dr. Bannister (private communication) feels that sterrettite is the more sensible choice, i.e. the name less likely to lead to confusion. Dr. Larsen (private communication) feels that eggonite has preference. Incidentally, the material from Fairfield seems to be a third generation mineral, having formed in cavities in pseudowavellite, an alteration product of variscite.

M.F.

Sitaparite

BRIAN MASON: Bixbyite from Långban. The identity of bixbyite and sitaparite. *Geol. Fören. Förhandl.* (Stockholm), **64**, 117-125 (1942).

Sitaparite from Sitapur, India, and from Postmasburg, South Africa, gave x-ray powder photographs identical with that of bixbyite from Långban. The optical and physical properties are also practically identical. The only analysis of sitaparite gave 6.1% CaO and it is not clear how the calcium is placed in the R_2O_3 structure.

DISCUSSION: Bixbyite and sitaparite were also found to be identical by Dr. Clifford Frondel of Harvard University (private communication, April, 1942). A new analysis of the Sitapur material seemed desirable, but the specimens available for study were found to contain numerous inclusions of ferromite. Could the 6% CaO reported by Fermor be due to admixed ferromite? This would mean that about 6% $\text{P}_2\text{O}_5 + \text{As}_2\text{O}_5$ was overlooked. A new analysis on pure material is needed. The name sitaparite should be dropped.

M.F.

Mangualdite

BRIAN MASON: Mangualdite is manganvoelckerite. *Geol. Fören. Förhandl.* (Stockholm), **63**, 383-386 (1941).

Mangualdite (de Jesus, 1933) from Mangualde, Portugal, gave an x-ray photograph

identical with that of maganoan apatite. The refractive indices ($\omega=1.646$, $\epsilon=1.642$) and G . (3.28) are inconsistent with the original analysis (CaO 17.75, MnO 31.47). Re-analysis of type material gave CaO 47.66, MnO 6.65, but showed a deficiency in (OH, F, Cl). The mineral is a manganoan oxyapatite or manganvoelckerite. The name mangualdite should be dropped.

DISCUSSION: Complete dehydration of hydroxyapatite is known to require extremely high temperatures. There is therefore some doubt as to the reality of the presence in large proportion of the oxyapatite or voelckerite molecule.

M.F.

Correction

Line 6, page 463, should read: "... some of which may be four, or more millimeters in length." In the original article "centimeters" was used.

Dr. T. L. Walker, professor emeritus of mineralogy and petrography of the University of Toronto, died Aug. 6, 1942. Dr. Walker served as Director of the Royal Ontario Museum of Mineralogy from 1913 to the time of his retirement in 1937. He was a charter fellow of the Mineralogical Society of America; in 1920 he was elected vice-president, and in 1922 president of the Society.